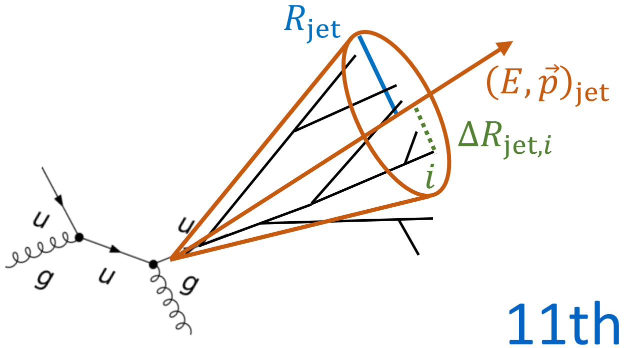
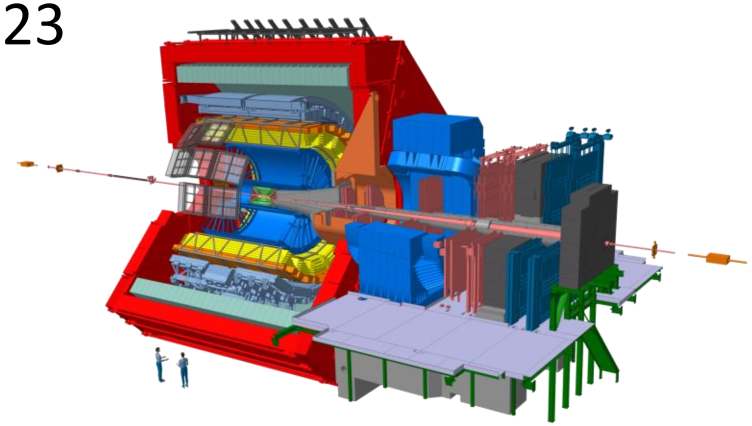
Measurement of the jet mass and jet angularities in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



Ezra D. Lesser (UC Berkeley)
on behalf of the ALICE collaboration

11th Int’l Conference on Hard and Electromagnetic Probes
28 March 2023



Quenched jet modification

- **How does the QCD medium affect jet formation?**

Quenched jet modification

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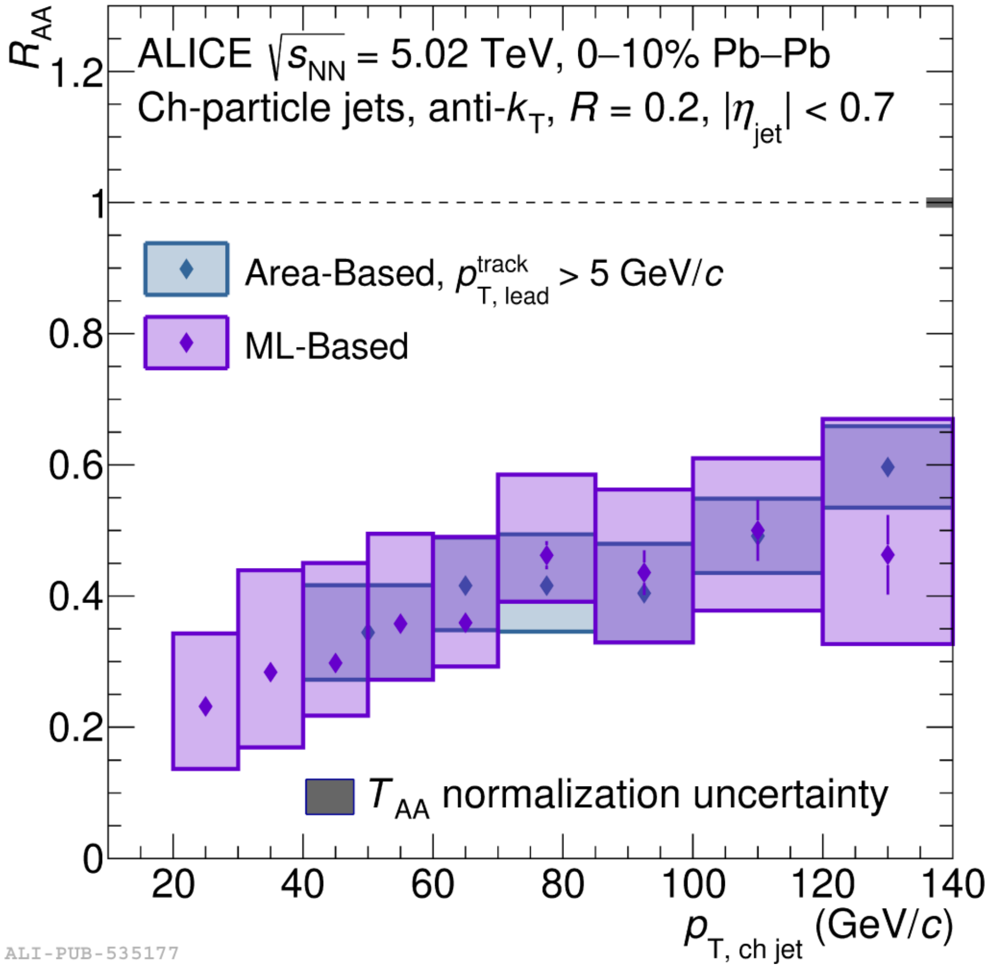

Christos Pliatskas (ALICE)

Earlier today at 09:00 (link)

arXiv:2303.00592 [nucl-ex]

- $R_{AA} < 1$ → jets are "quenched" by QGP
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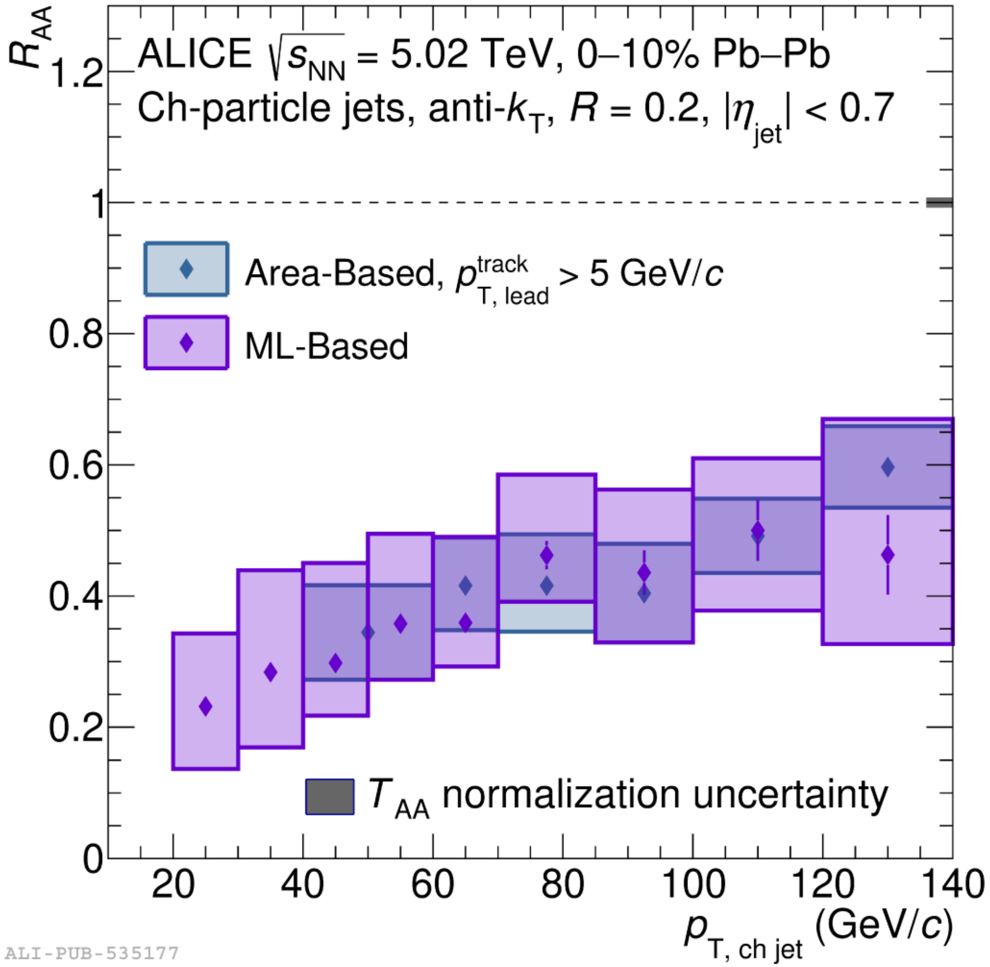

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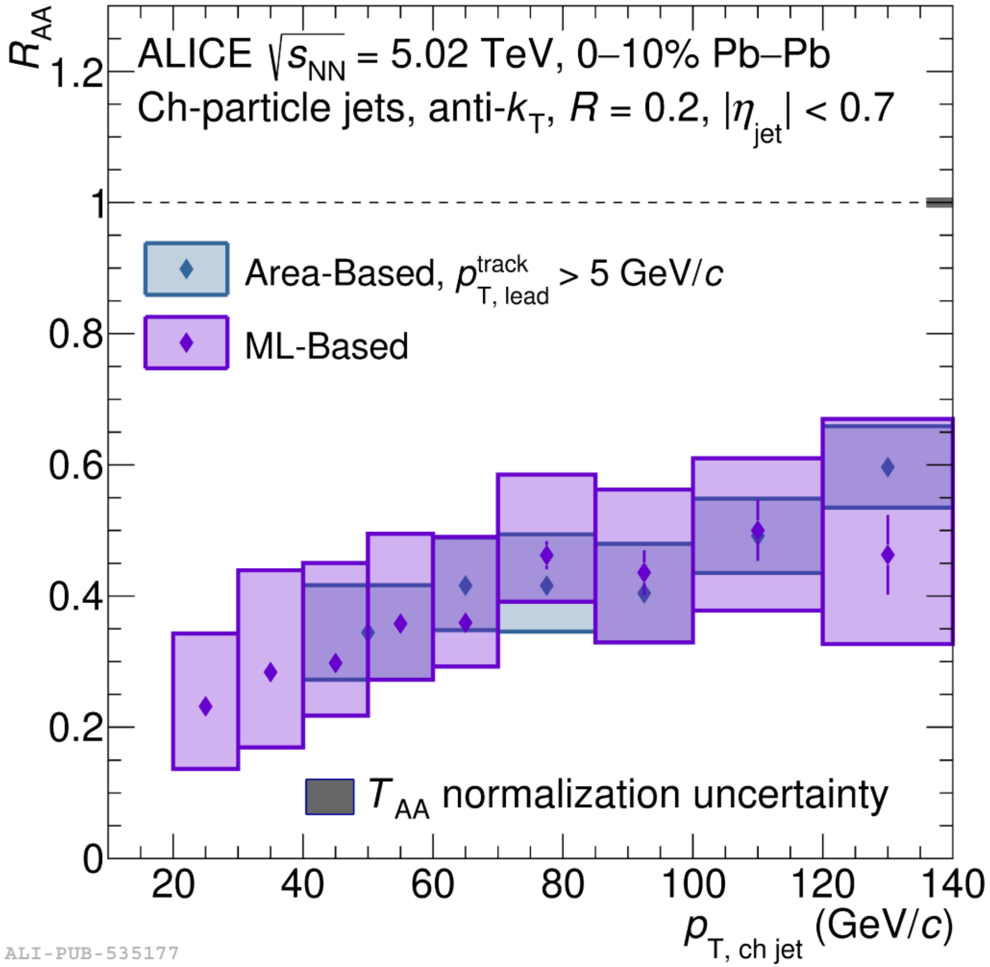

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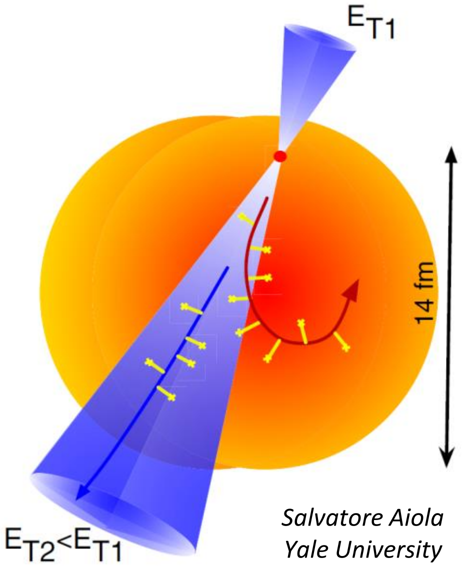

Salvatore Aiola
Yale University

- **Jet substructure** gives insight into the microscopic modification
- Choose observables based on desired probe

Generalized jet angularities ($\lambda_{\alpha}^{\kappa}$)

A. Larkoski, J. Thaler, W. Waalewijn
JHEP 11 (2014) 129

- **Class of substructure observables** dependent on $\boldsymbol{p}_{\mathbf{T}}$ and **angular** distributions of jet constituents

$$\lambda_{\alpha}^{\kappa} \equiv \sum_{i \in \mathrm{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}\right)^{\kappa} \left(\frac{\Delta R_{i,\mathrm{jet}}}{R}\right)^{\alpha}$$

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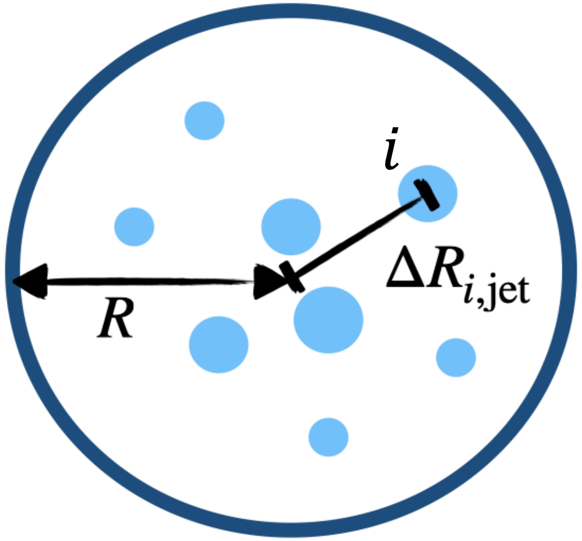

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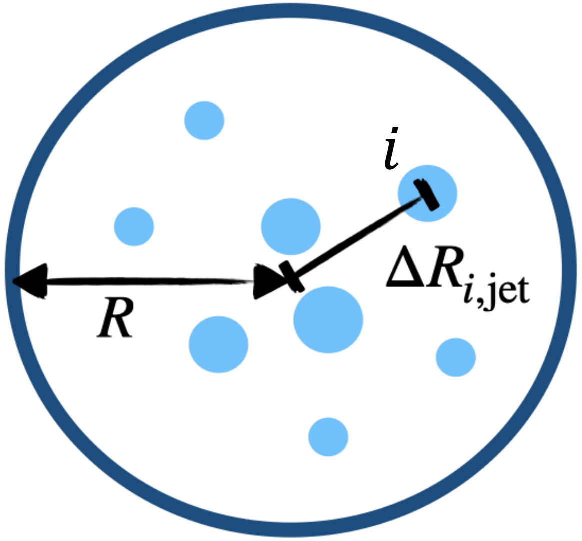
Tunable, continuous parameters for relative weighting

Constituent angle in (η, ϕ) space

Constituent p_T



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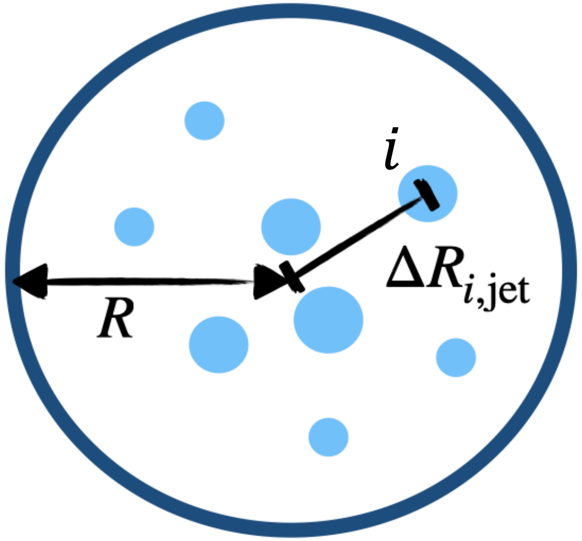

- IRC-safe* observable for $\kappa = 1$, $\alpha > 0$ → vacuum is calculable from pQCD
- Each (κ, α), R defines a different observable capable of probing jet structure and providing systematic constraints on theory
- Generalizes other observables: **jet girth** $g = \lambda_1^1$; **jet thrust** $= \lambda_2^1$; …

---

* *track-based observables IRC-unsafe (see backup)*

Jet angularity vs. mass modification

$$\lambda_\alpha \equiv \sum_{i\in\text{jet}} z_i \theta_i^\alpha$$

- The **jet angularities** are related to the **jet mass**:

Z.-B. Kang, K. Lee, F. Ringer
JHEP 1804 (2018) 110 (eq'n 2.6) → **Jet thrust** $\lambda_2 = \left(\frac{m}{Rp_\mathrm{T}}\right)^2 + O[(\lambda_2)^2]$

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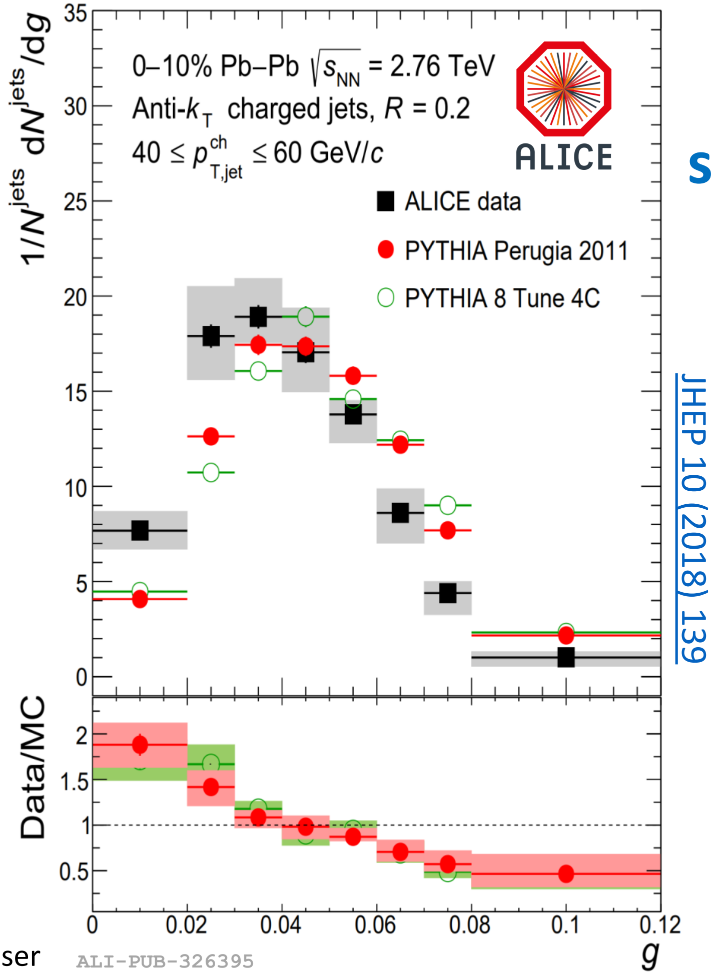

JHEP 10 (2018) 139

$\alpha = 1, R = 0.2$

significant modification

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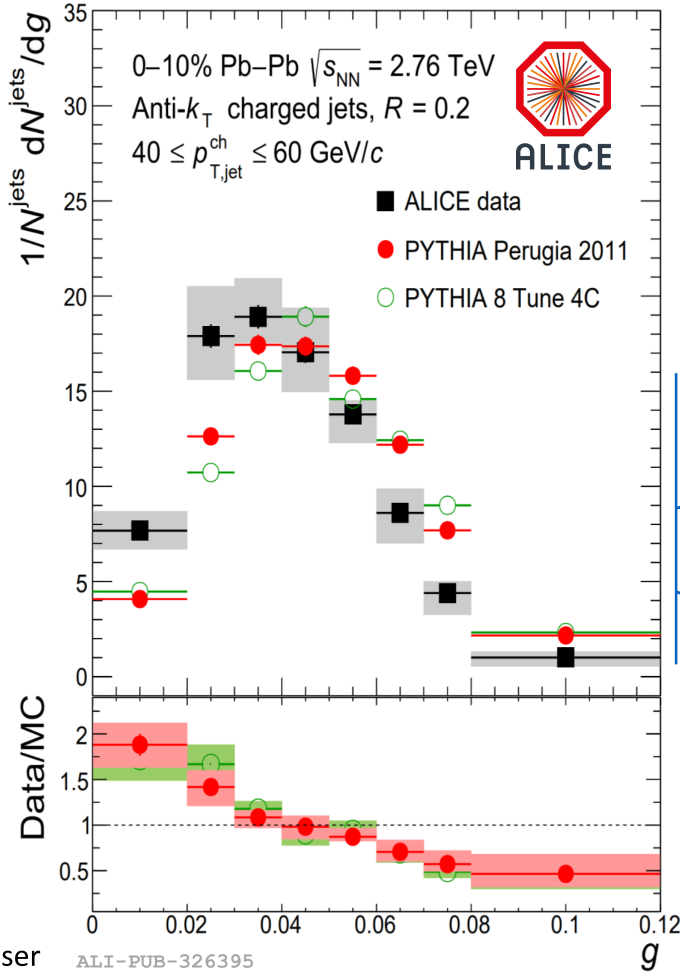
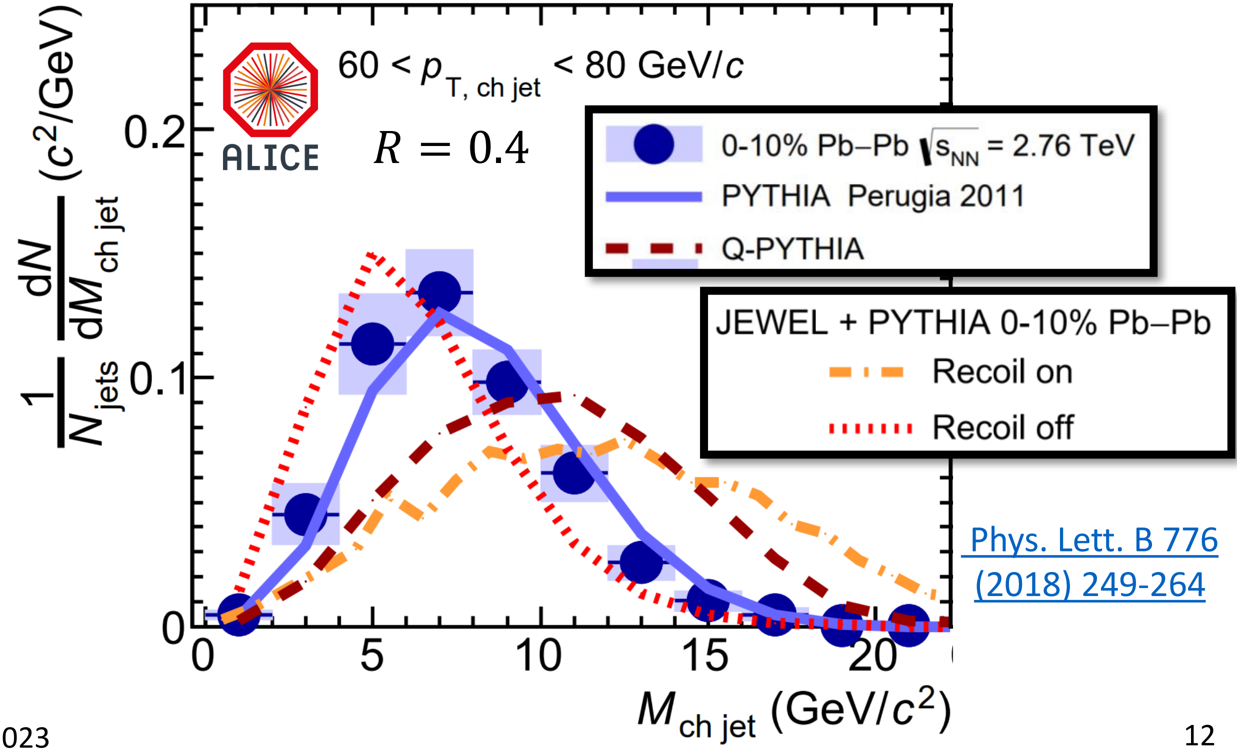


JHEP 10 (2018) 139

$\alpha = 1, R = 0.2$
significant modification

$\alpha = 2, R = 0.4$
no significant modification



Phys. Lett. B 776 (2018) 249-264

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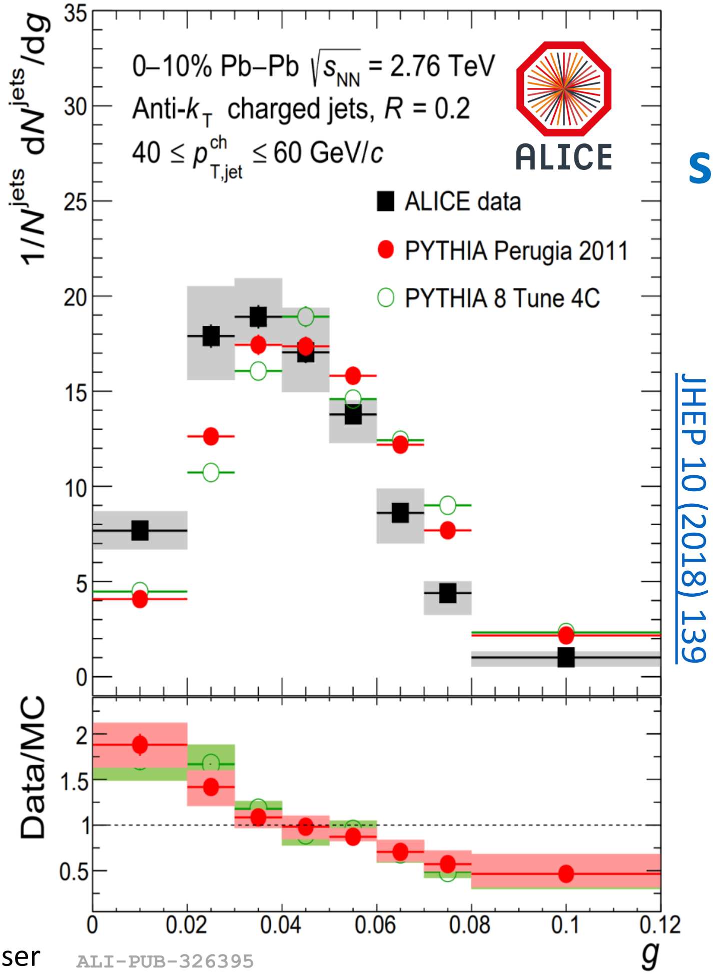

JHEP 10 (2018) 139

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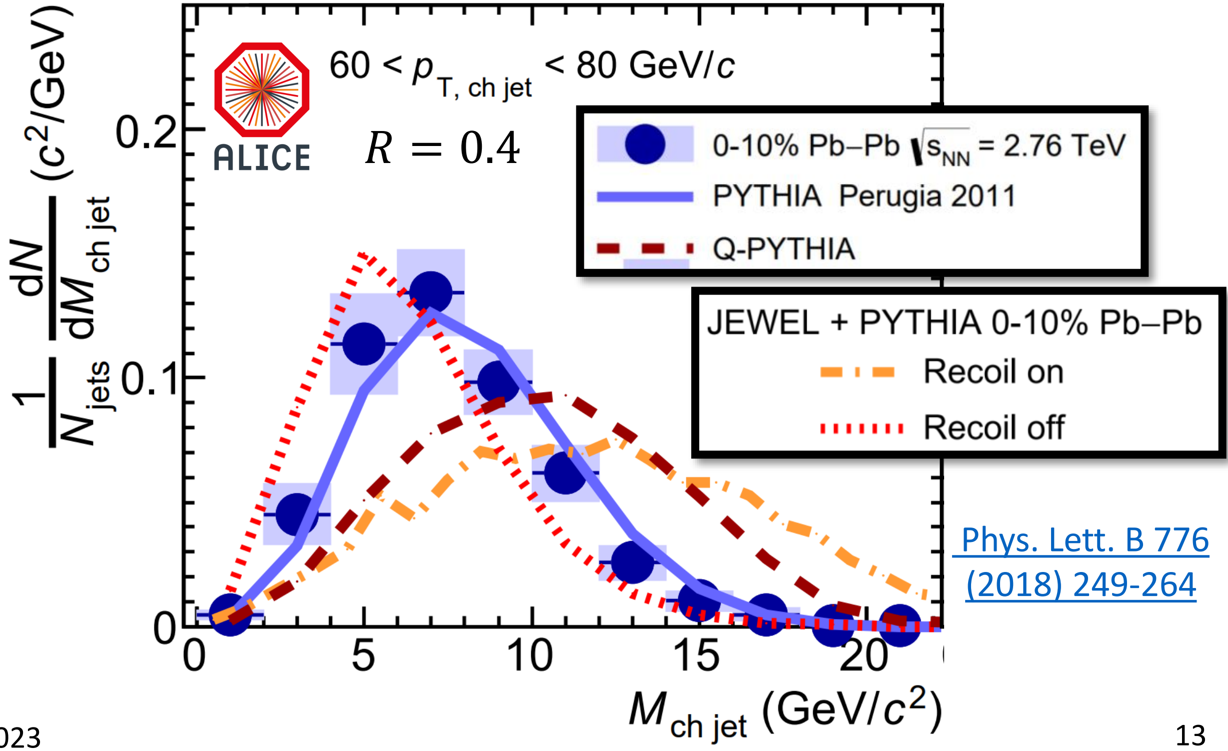
- *"Girth-mass puzzle"*
- **What's the difference?** $R, p_\mathrm{T}^\mathrm{jet}, \alpha$…



Phys. Lett. B 776 (2018) 249-264

Systematic measurement of angularities

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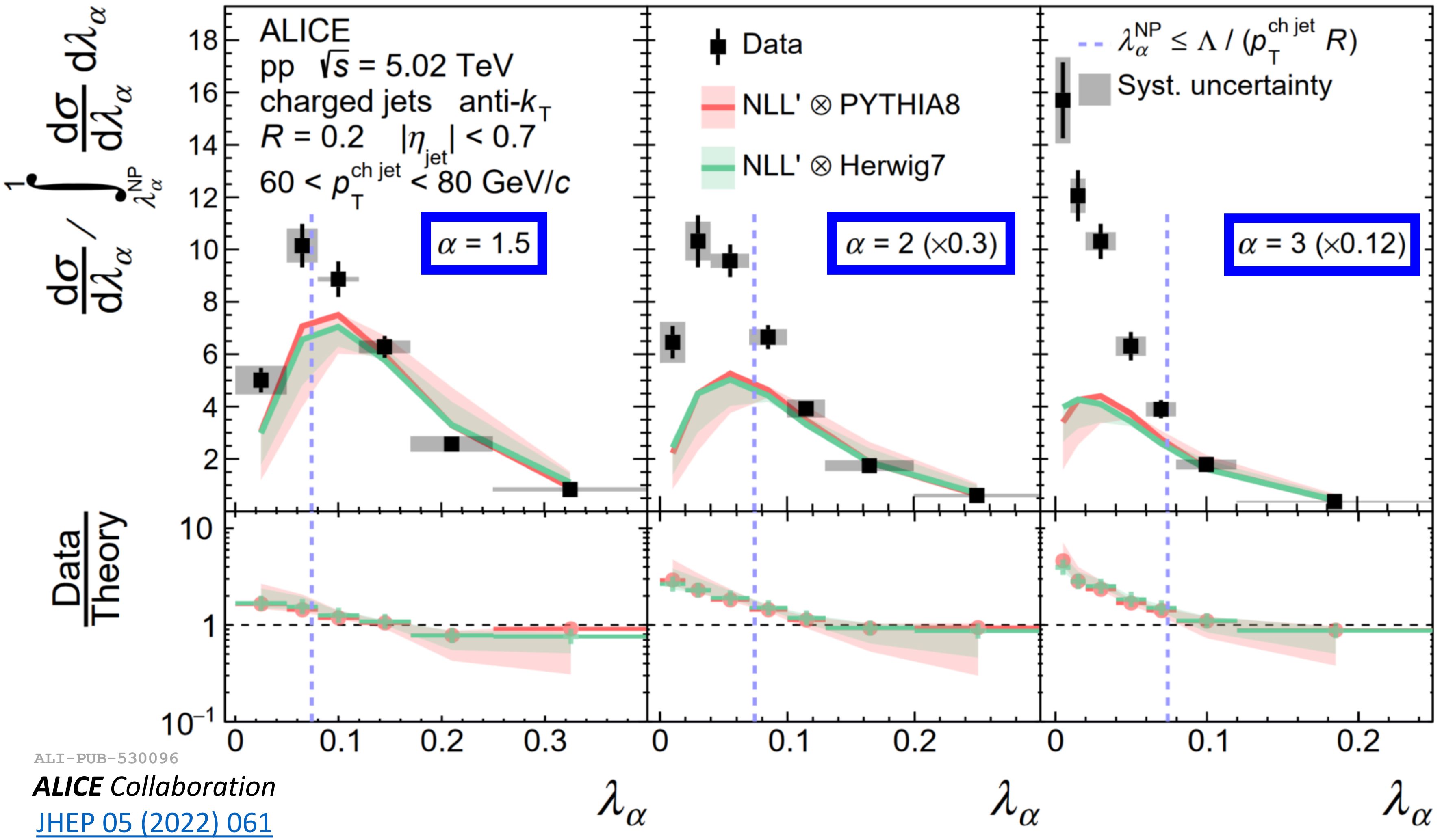
- Measurements in pp **compared to pQCD predictions**



ALICE Collaboration
JHEP 05 (2022) 061

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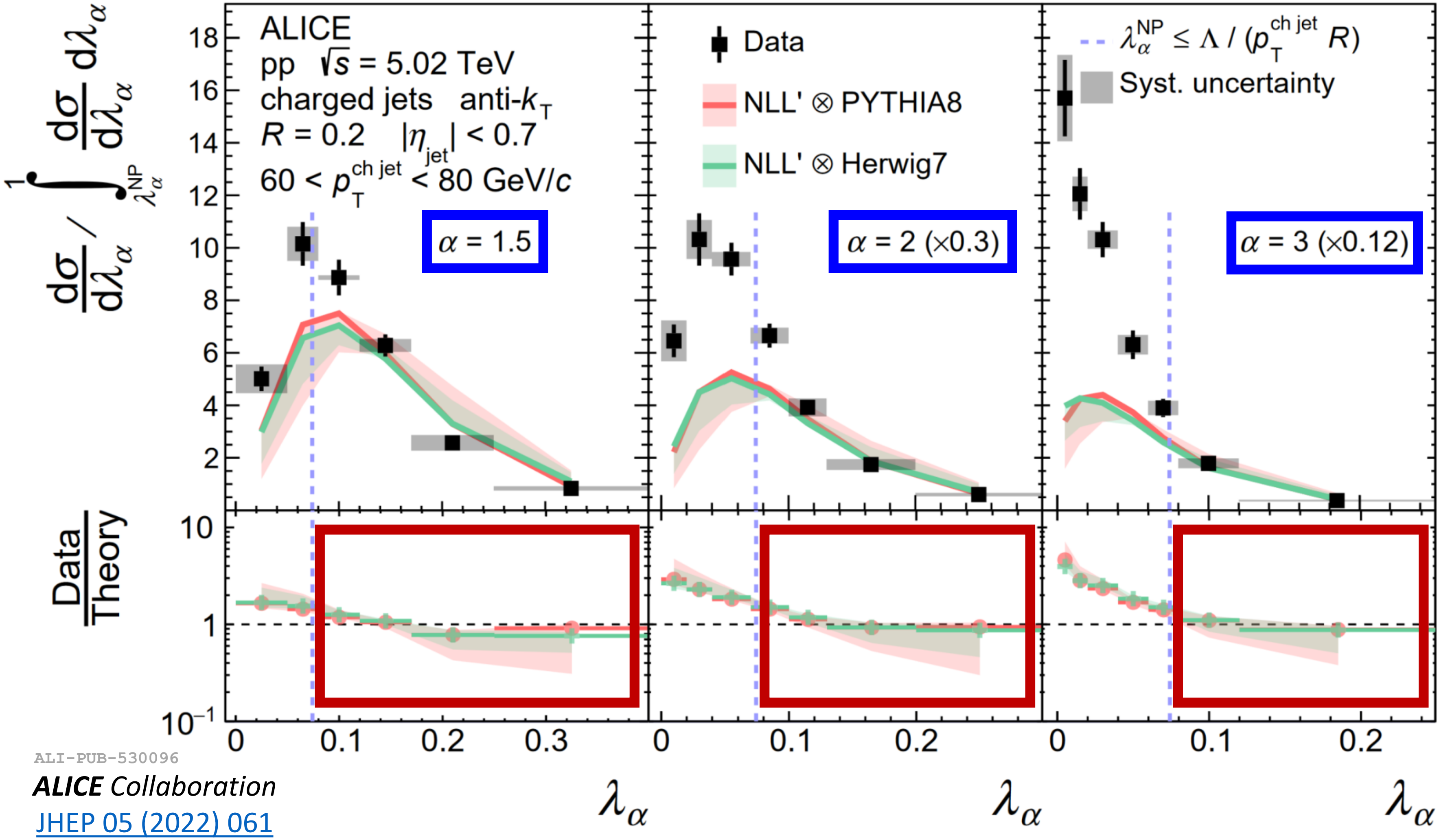

- **Agreement in perturbative region**

ALICE Collaboration
JHEP 05 (2022) 061

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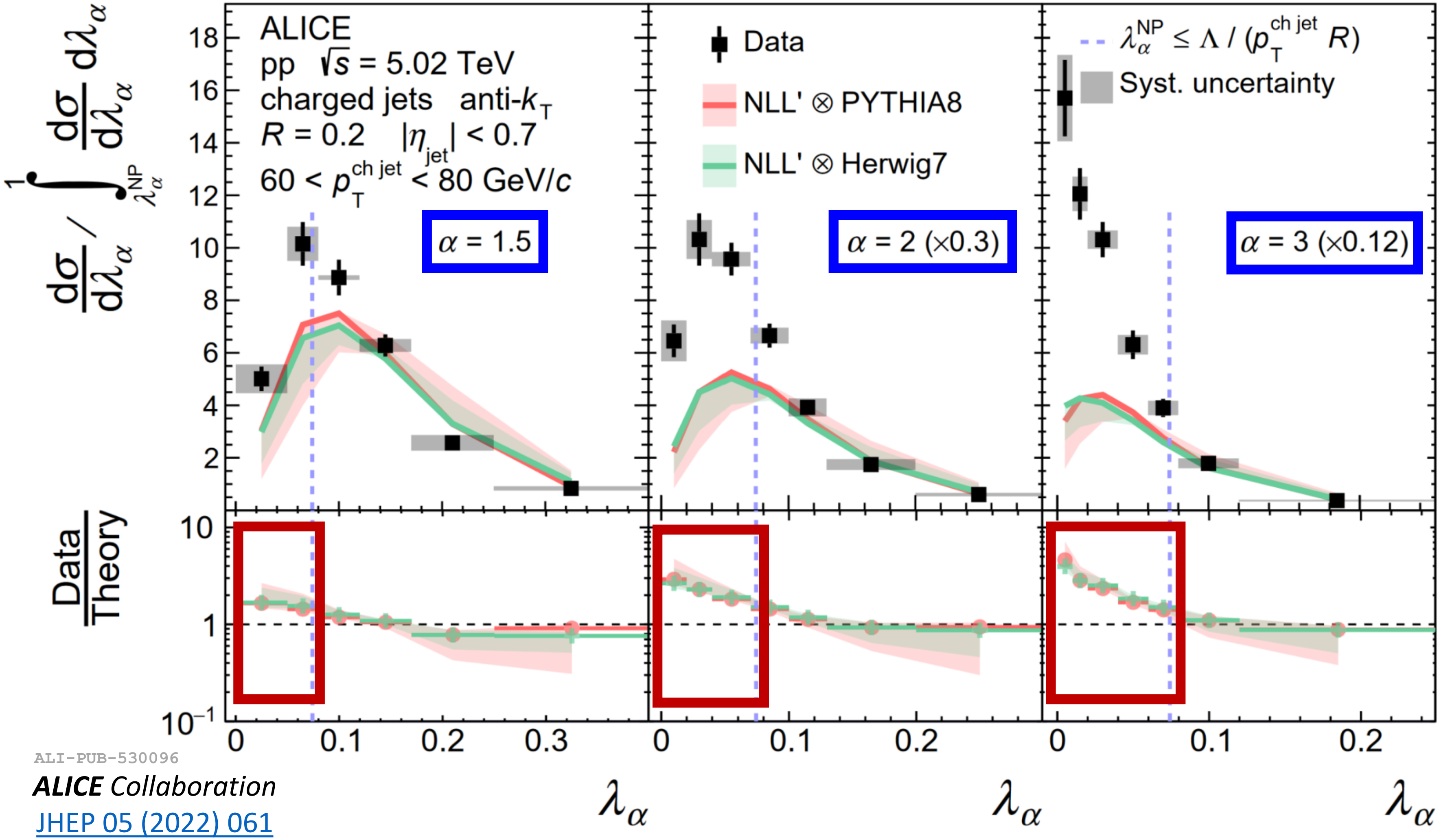

- **Agreement in perturbative region**
- **Disagreement in nonperturbative region (as expected)**

***ALICE** Collaboration*
JHEP 05 (2022) 061

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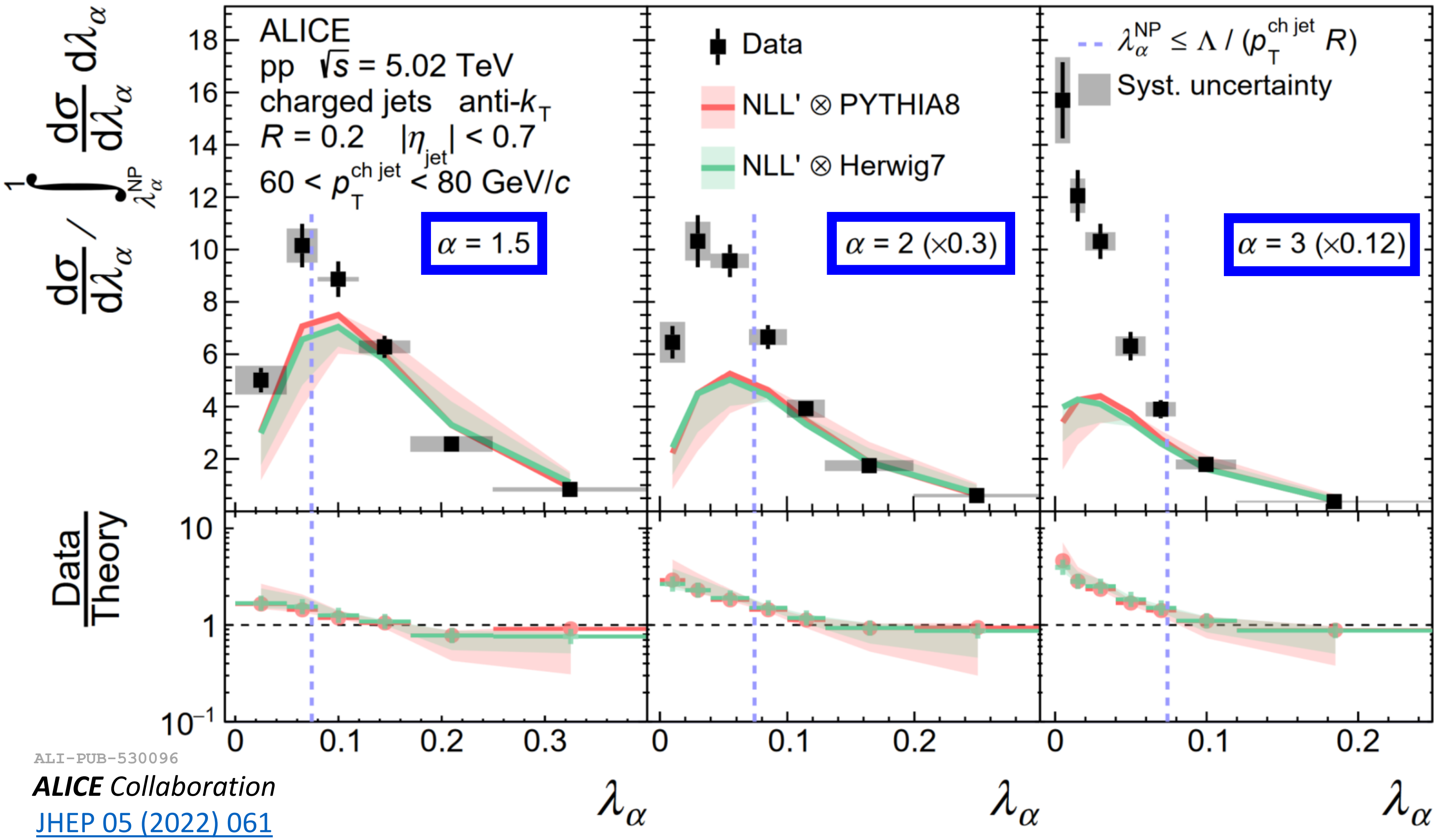
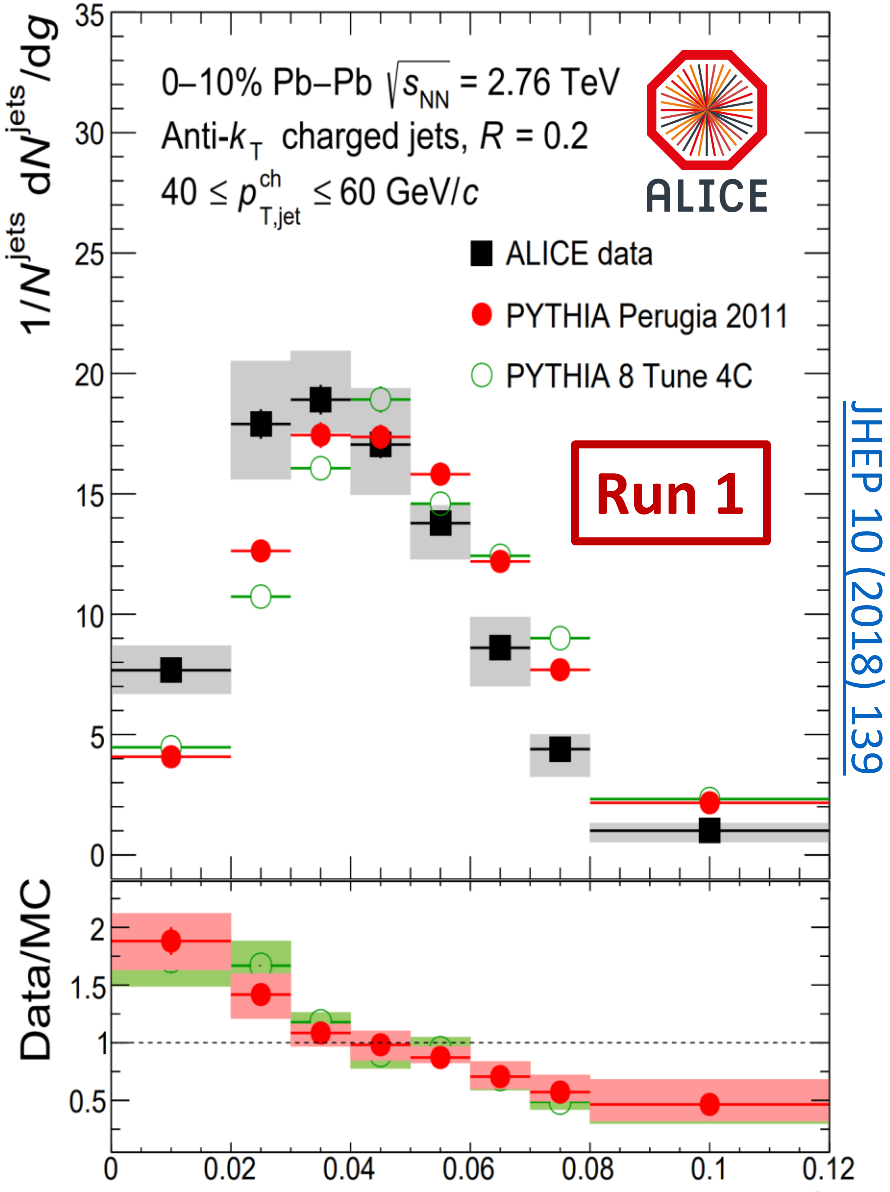


***ALICE** Collaboration*
JHEP 05 (2022) 061

- **Agreement in perturbative region**
- **Disagreement in nonperturbative region (as expected)**
- **Varying physics sensitivities for different α, R, p_T**
- **Improved baseline for Pb-Pb studies**

Z.-B. Kang, K. Lee, F. Ringer
JHEP 1804 (2018) 110

Run 2 improved girth study



Run 1

JHEP 10 (2018) 139

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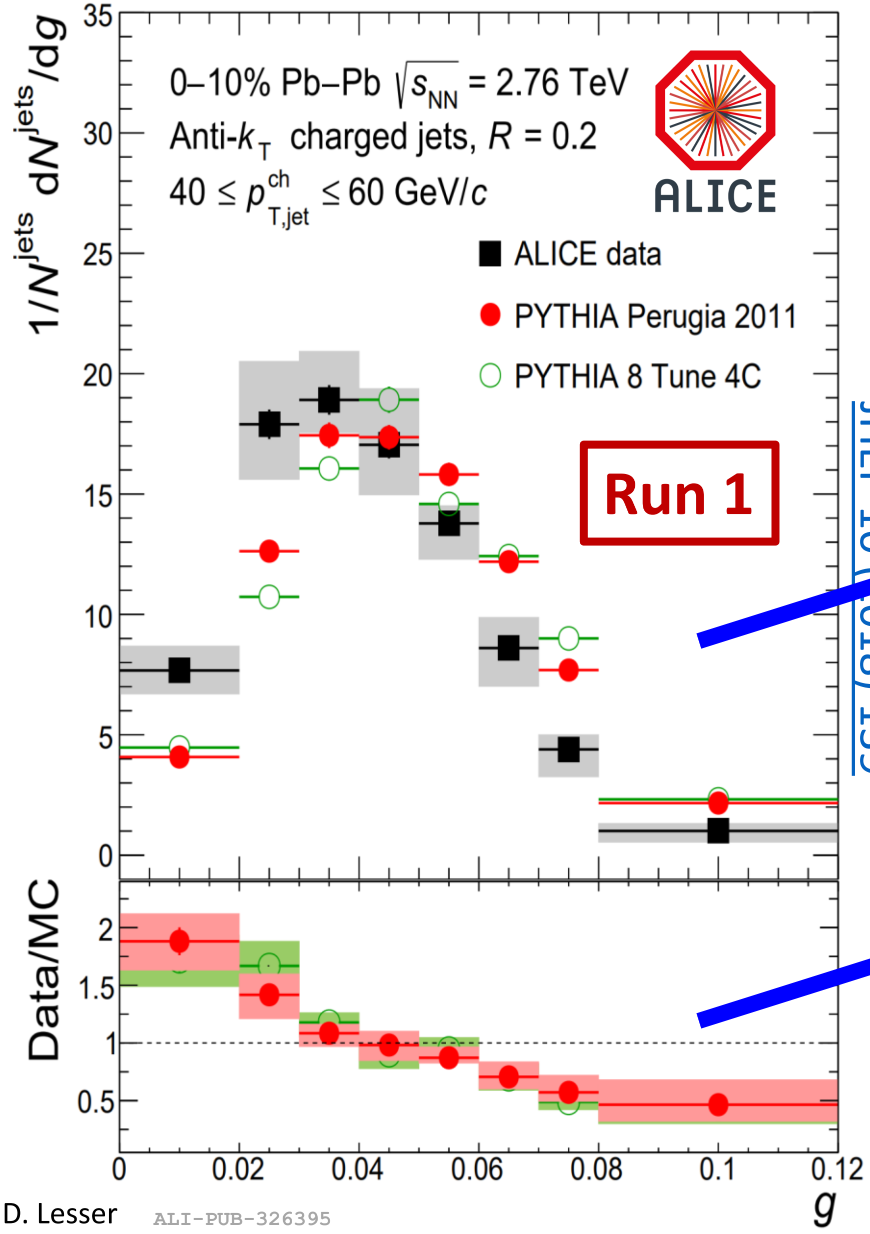
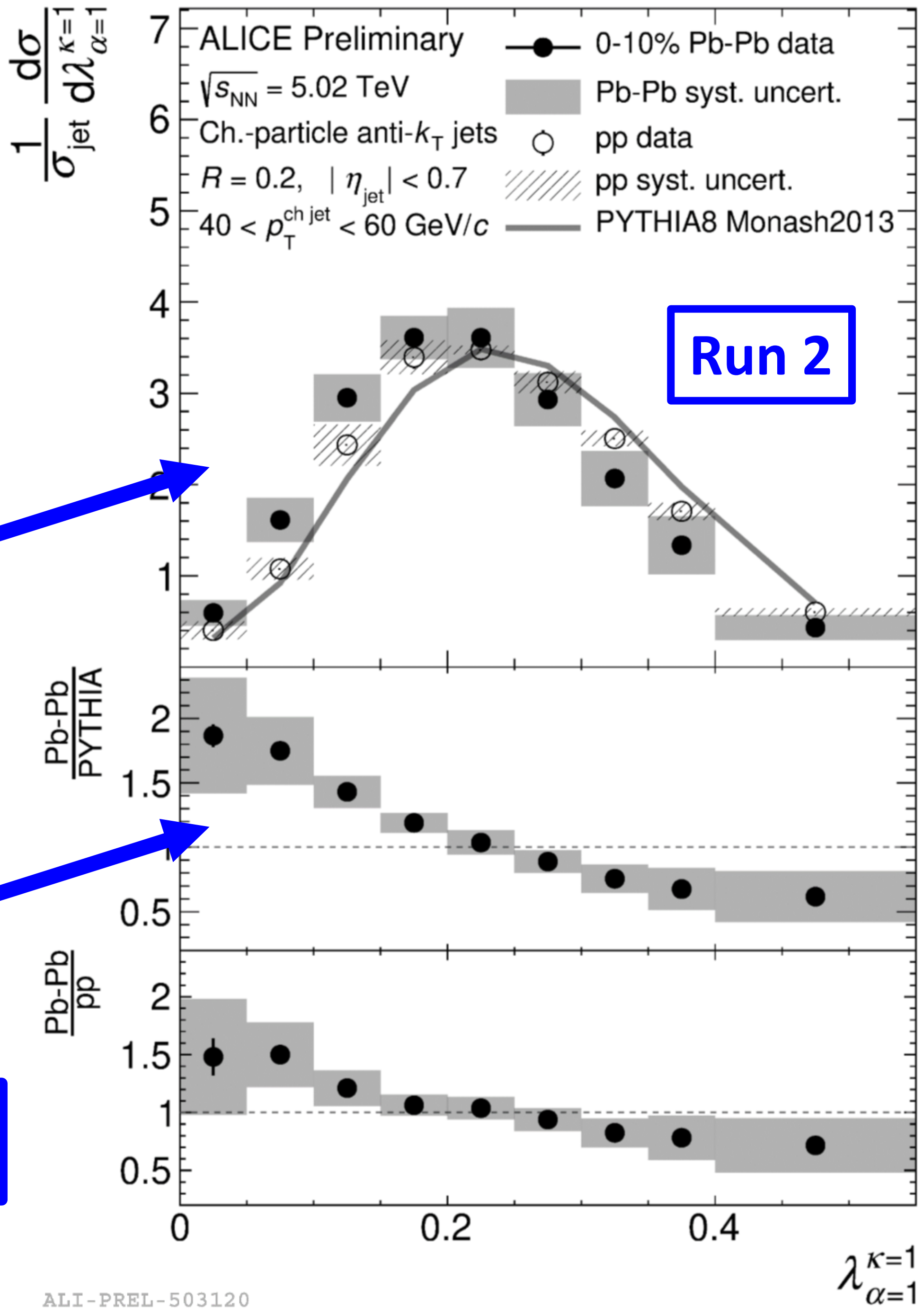


ALI-PUB-326395

JHEP 10 (2018) 139

$$\lambda_\alpha \equiv \sum_{i\in\text{jet}} z_i\theta_i^\alpha$$

$$\boxed{g = \lambda_1 * R}$$



ALI-PREL-503120

https://alice-figure.web.cern.ch/node/21570

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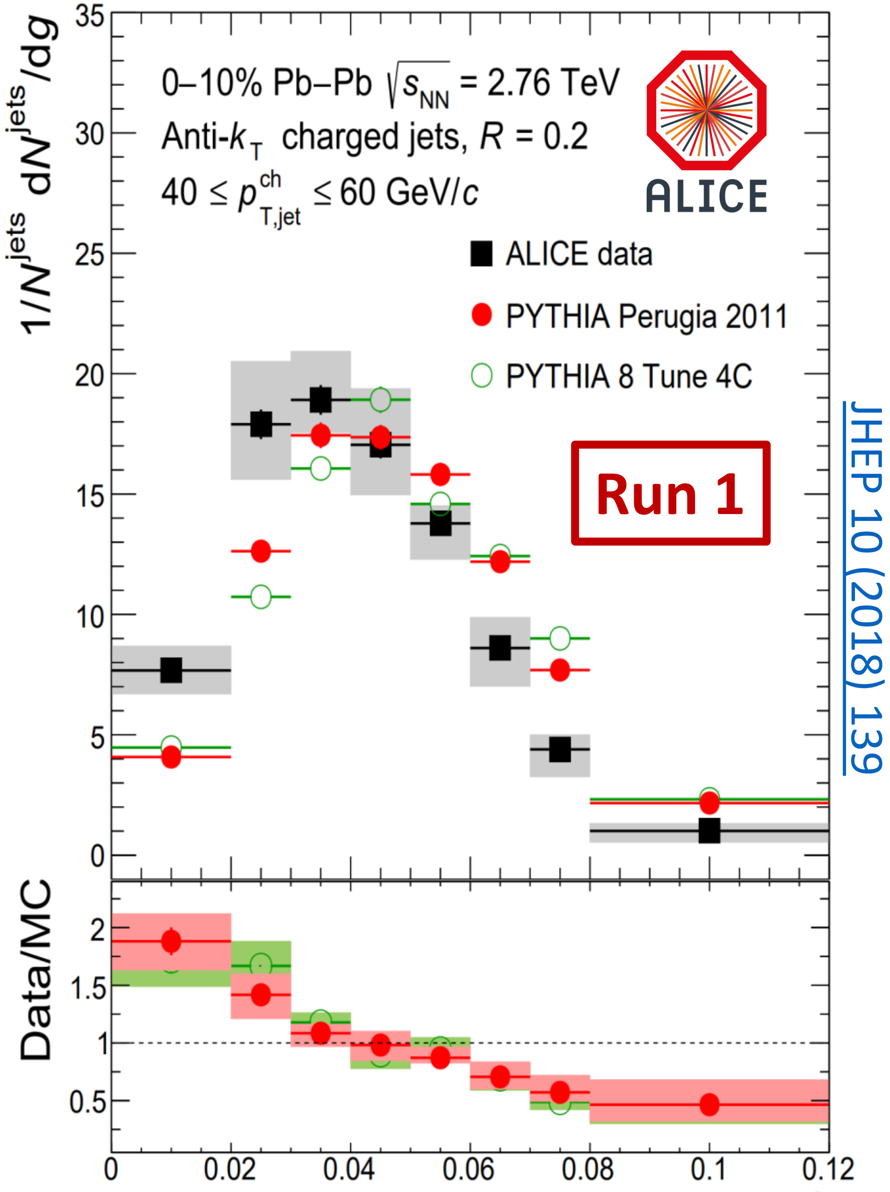

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JHEP 10 (2018) 139

ALI-PUB-326395

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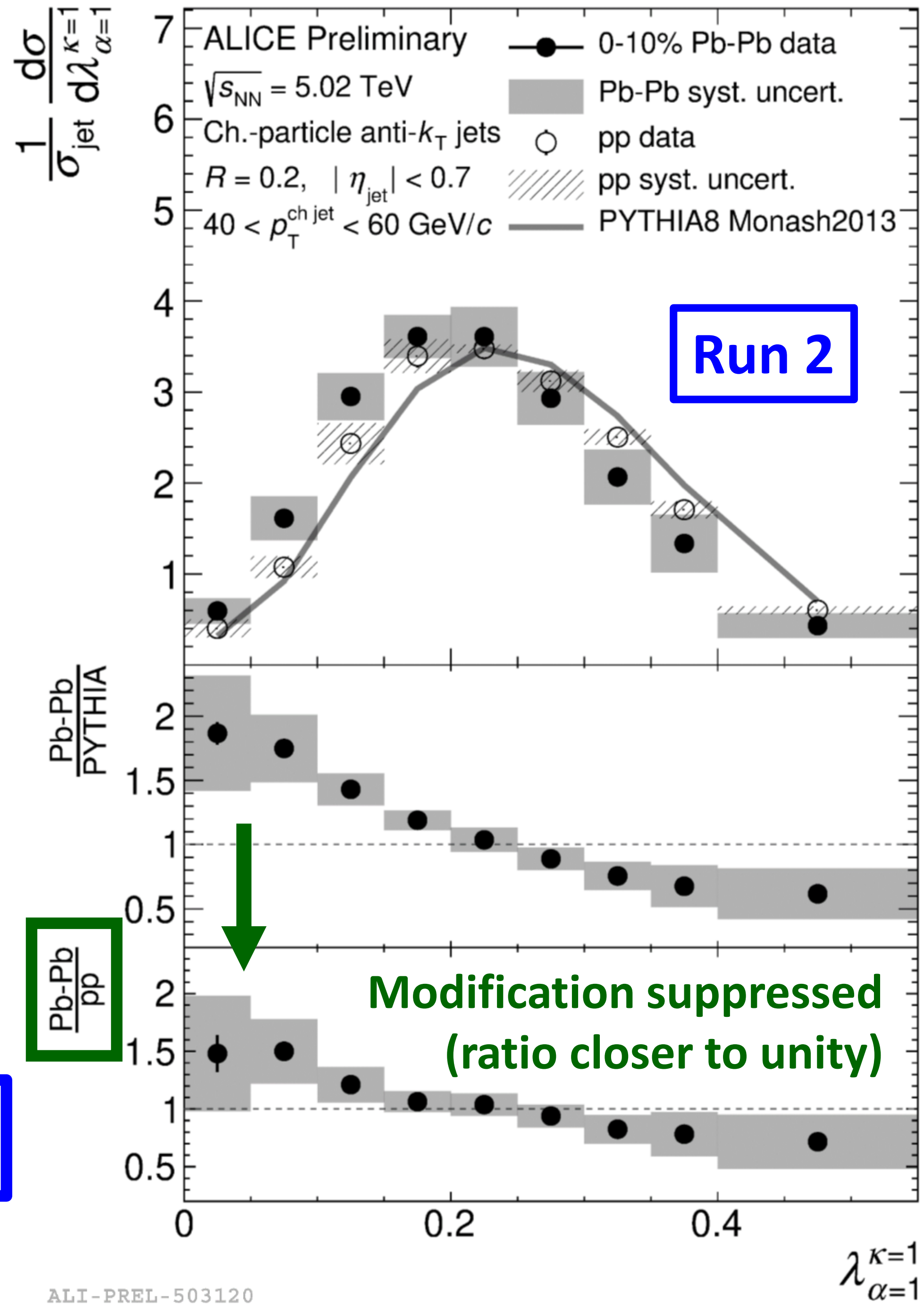


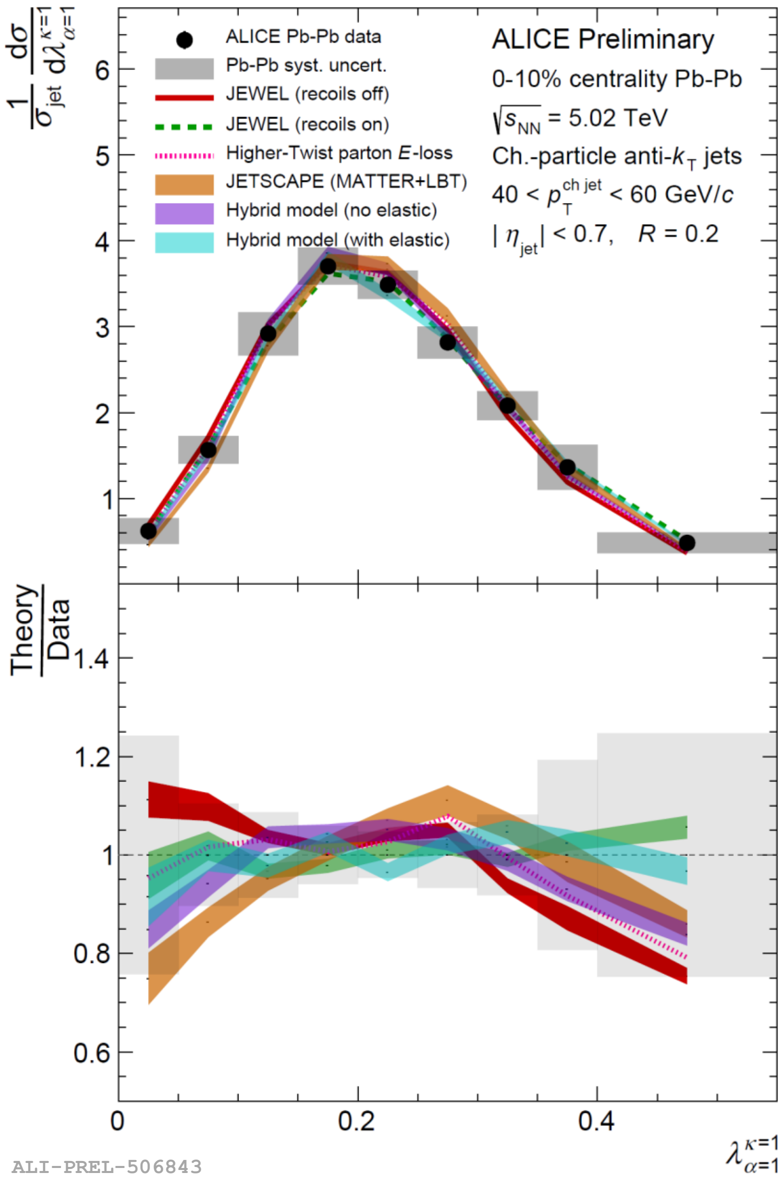
Run 2

Modification suppressed (ratio closer to unity)

ALI-PREL-503120

https://alice-figure.web.cern.ch/node/21570

Pb-Pb angularities compared with models $\lambda_\alpha \equiv \sum_{i\in\text{jet}} z_i\theta_i^\alpha$



https://alice-figure.web.cern.ch/node/21570

- **JEWEL** with recoils off / on
  - "Recoils on" uses negative energy recombiner scheme

K. Zapp, JHEP 1804 (2018) 110

- **JETSCAPE (MATTER + LBT)**

arXiv:2204.01163 [hep-ph]

- **Higher-Twist partonic energy loss**

S.-Y. Chen, B.-W. Zhang, et al., CPC 45 (2021) 2, 024102

- **Hybrid model** with / without elastic **Molière scattering**

D. Pablos, et al., JHEP 10 (2014) 019

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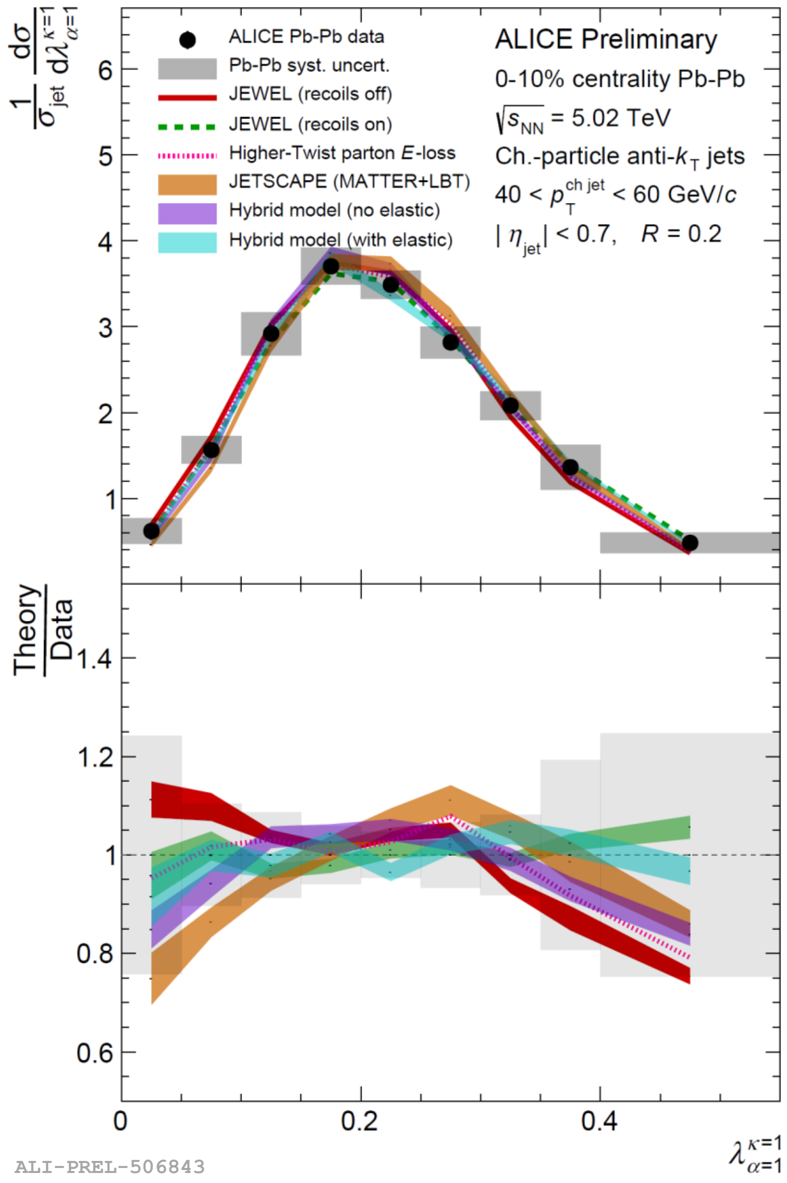

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- **Models are within uncertainties on Pb-Pb data…**

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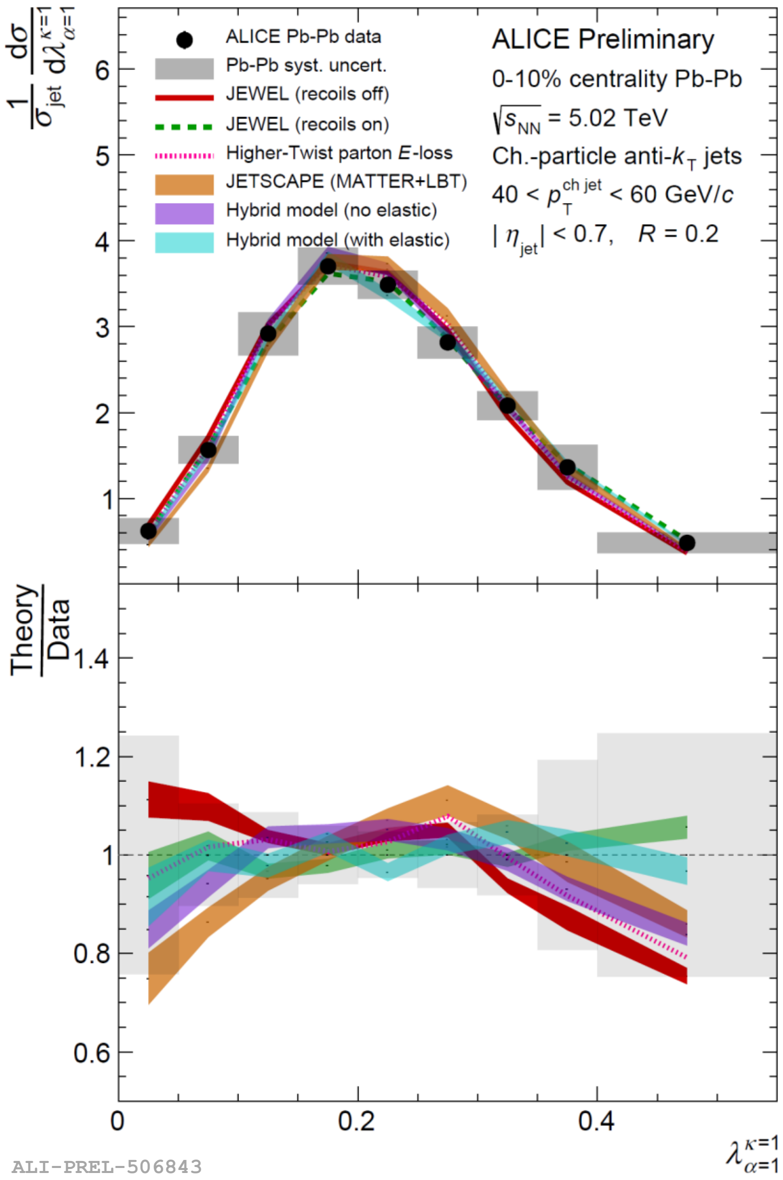

ALI-PREL-506843

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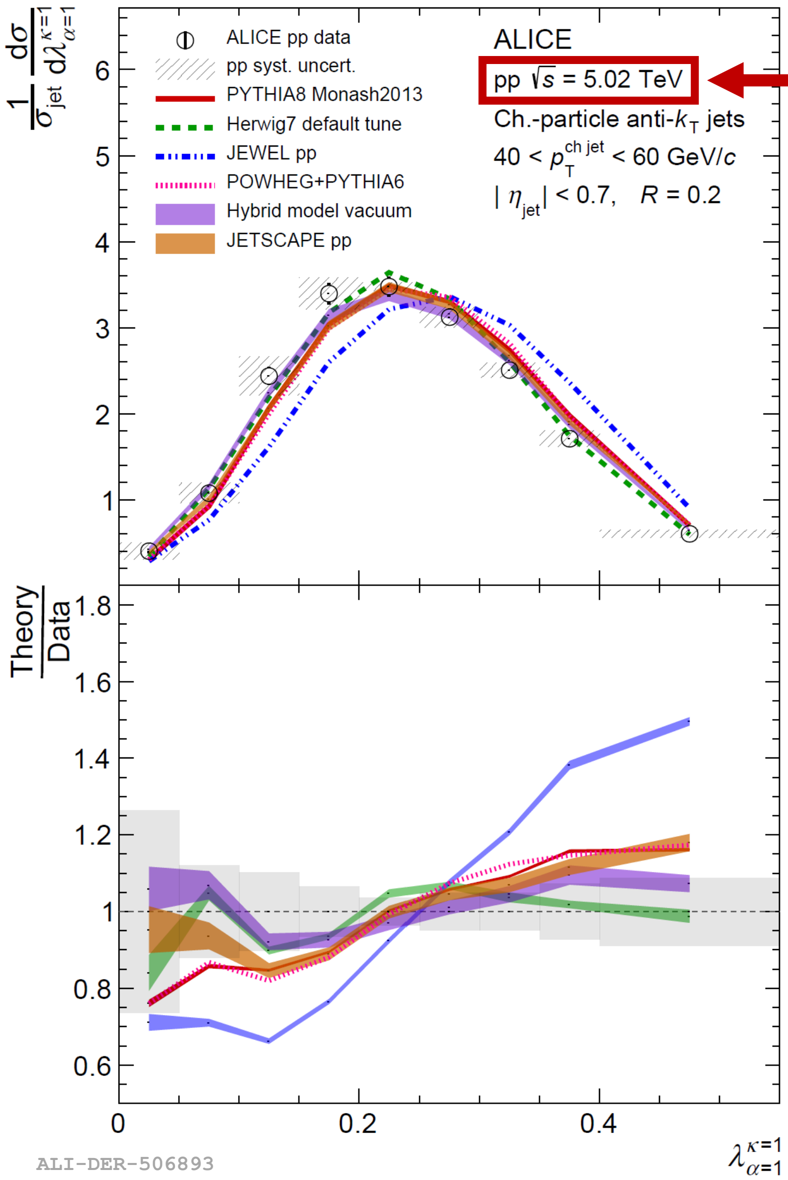

ALI-DER-506893

Run 2 pp baseline for AA quenching

Pb-Pb angularities compared with models

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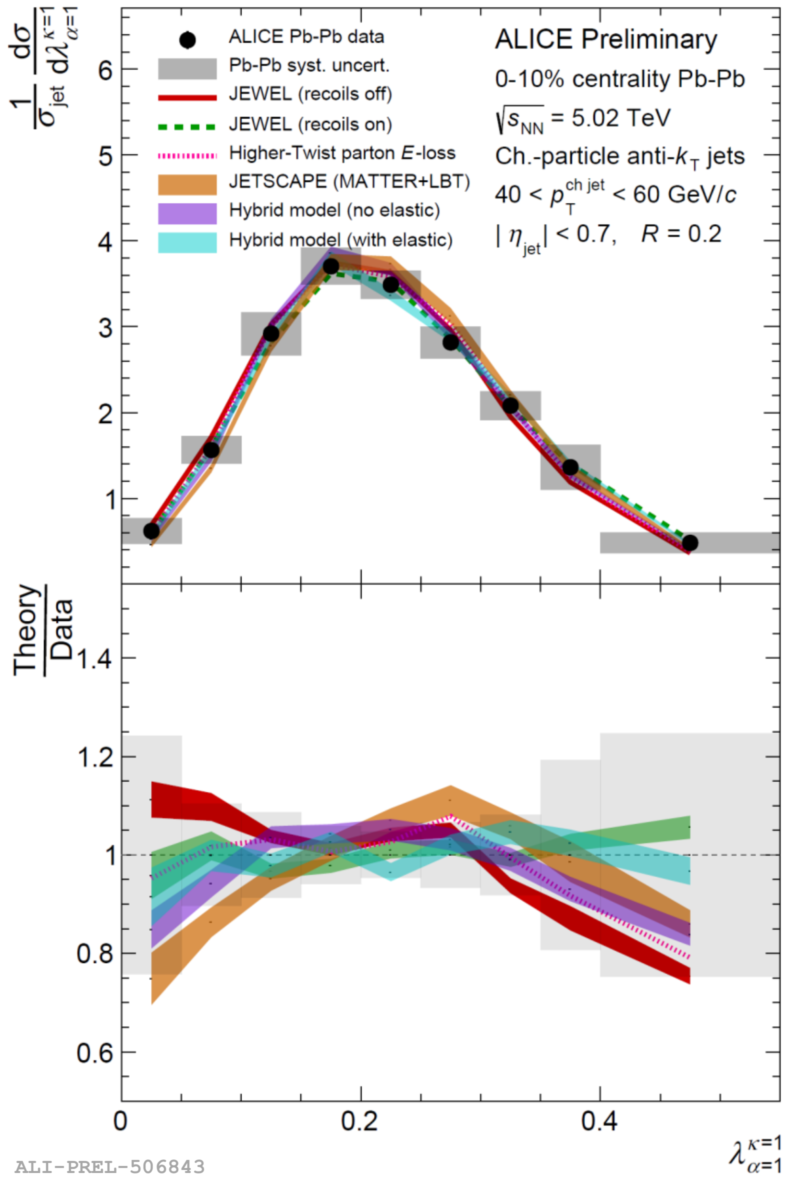

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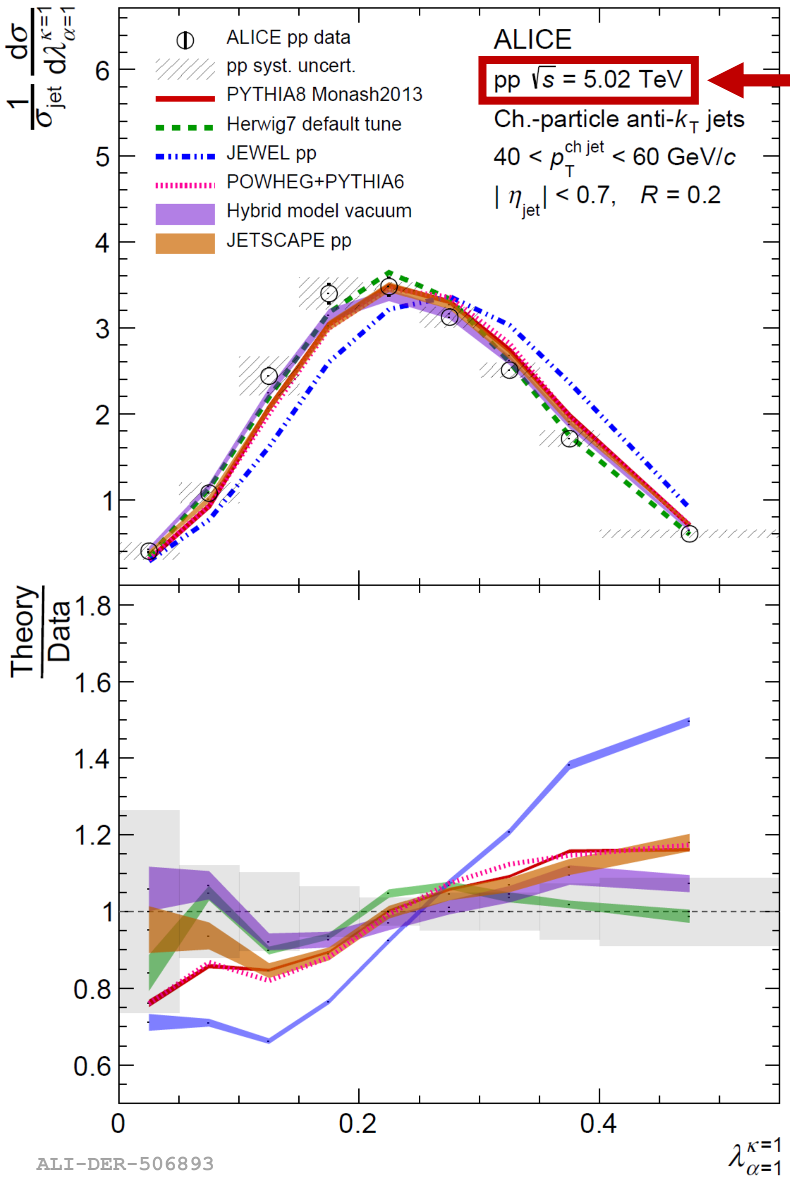

Run 2 pp baseline for AA quenching

Some models exhibit more tension in pp baseline than in AA

Pb-Pb angularities compared with models

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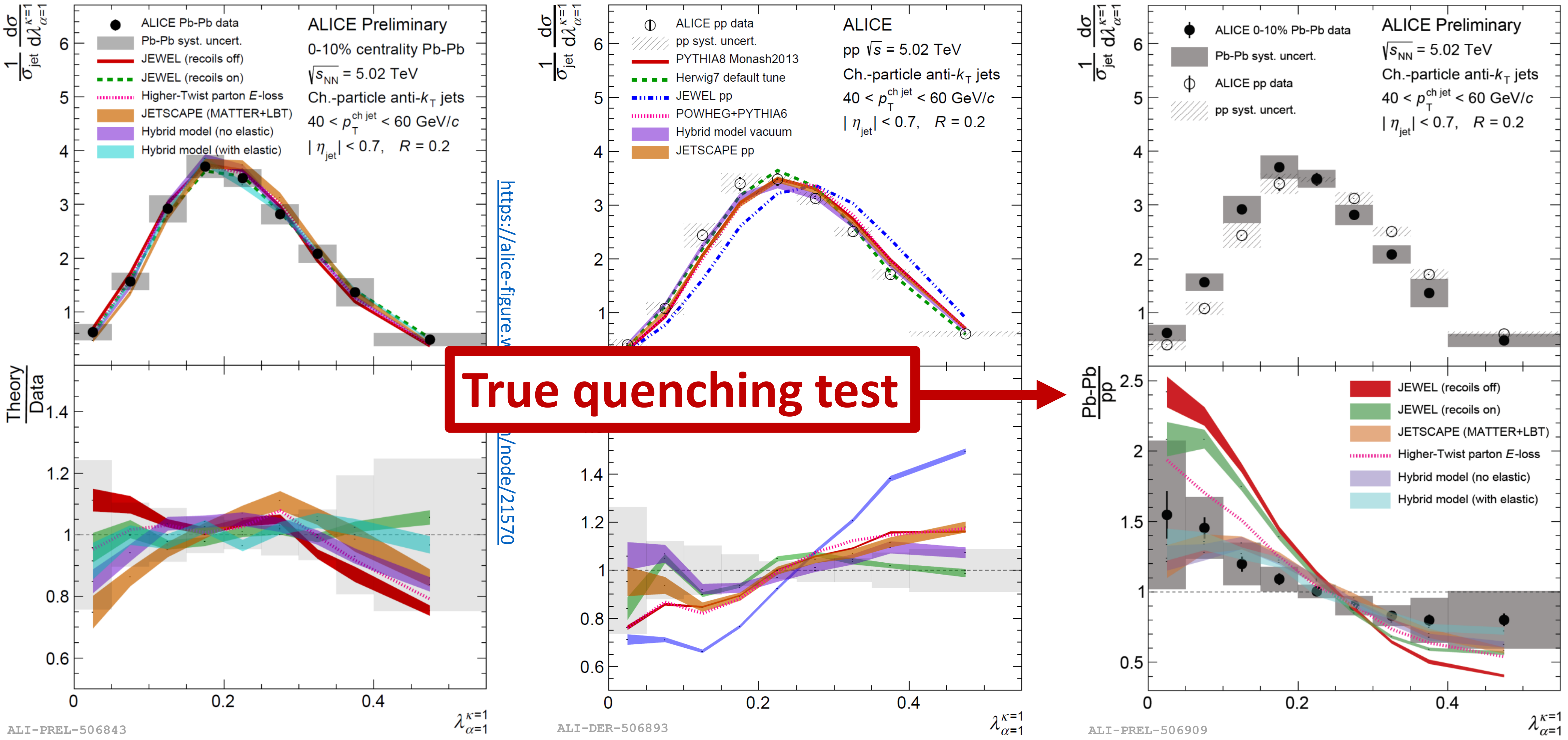

True quenching test

Pb-Pb angularities compared with models

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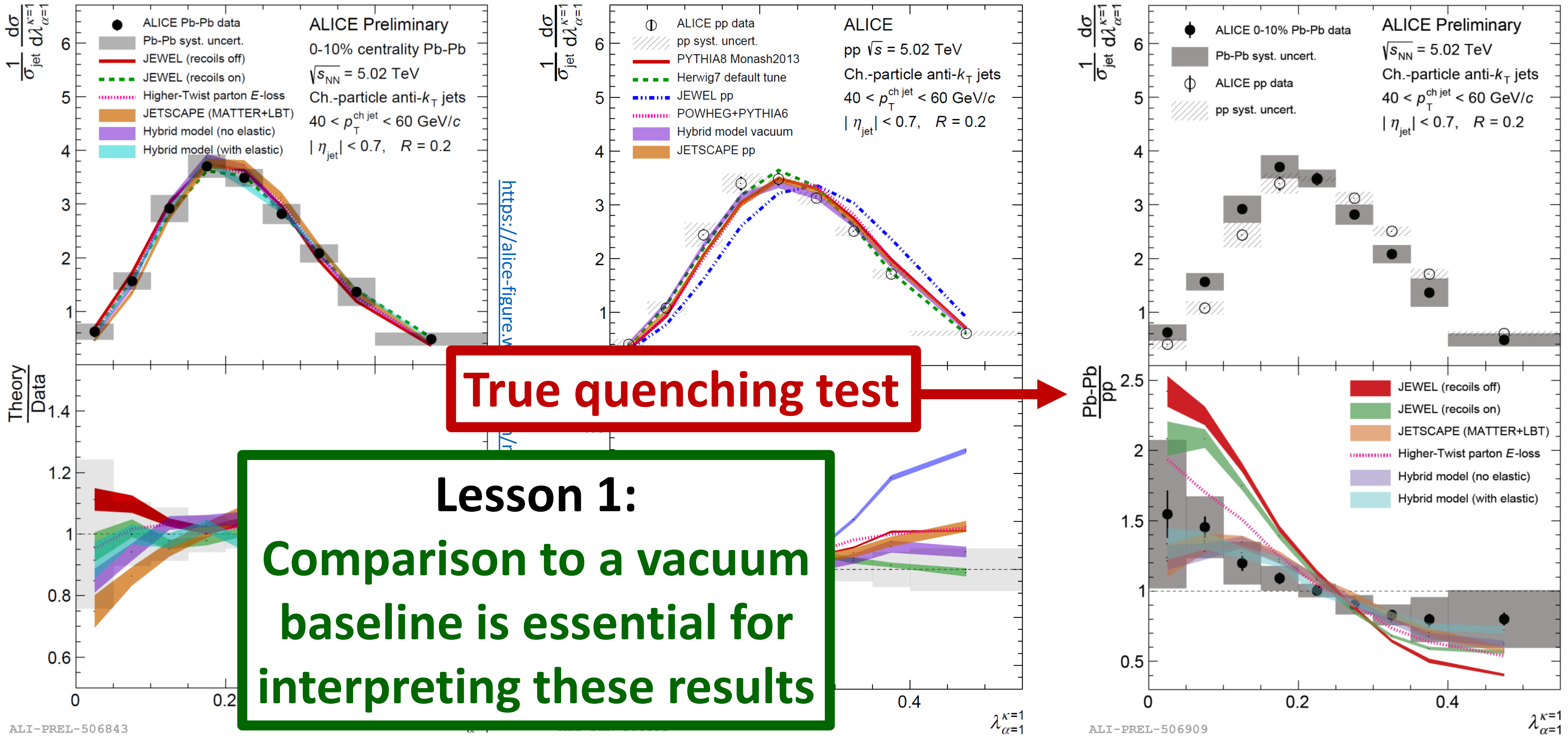


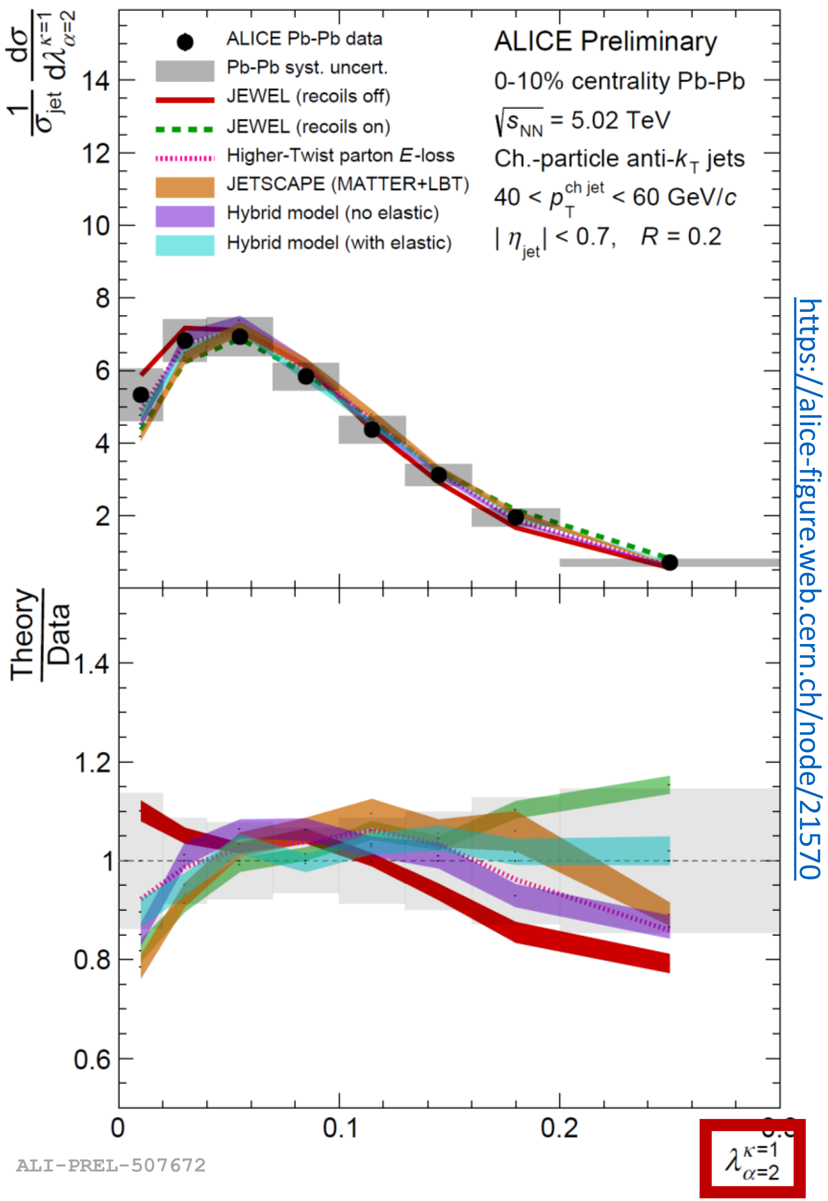
True quenching test

Lesson 1:

Comparison to a vacuum baseline is essential for interpreting these results

Pb-Pb thrust ($\alpha = 2$)

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$



ALI-PREL-507672

https://alice-figure.web.cern.ch/node/21570

Pb-Pb thrust ($\alpha = 2$) vs. jet mass **NEW!**

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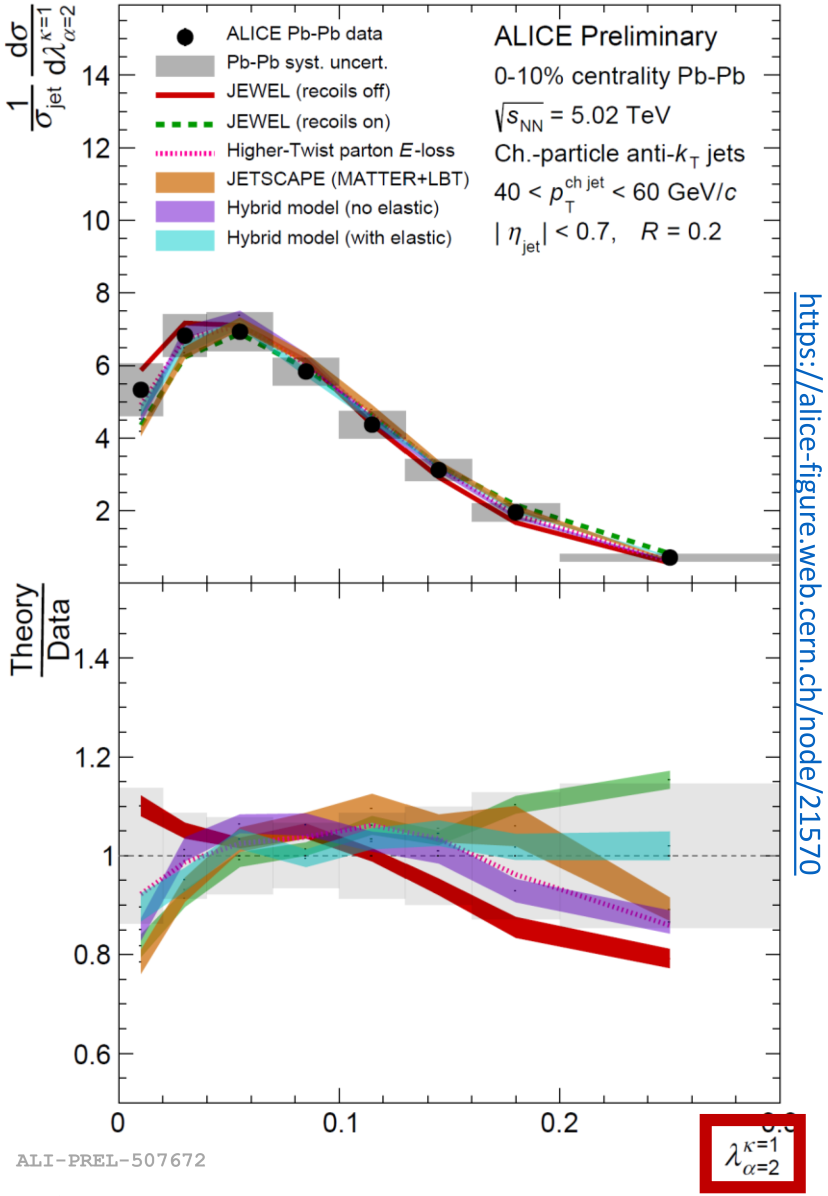
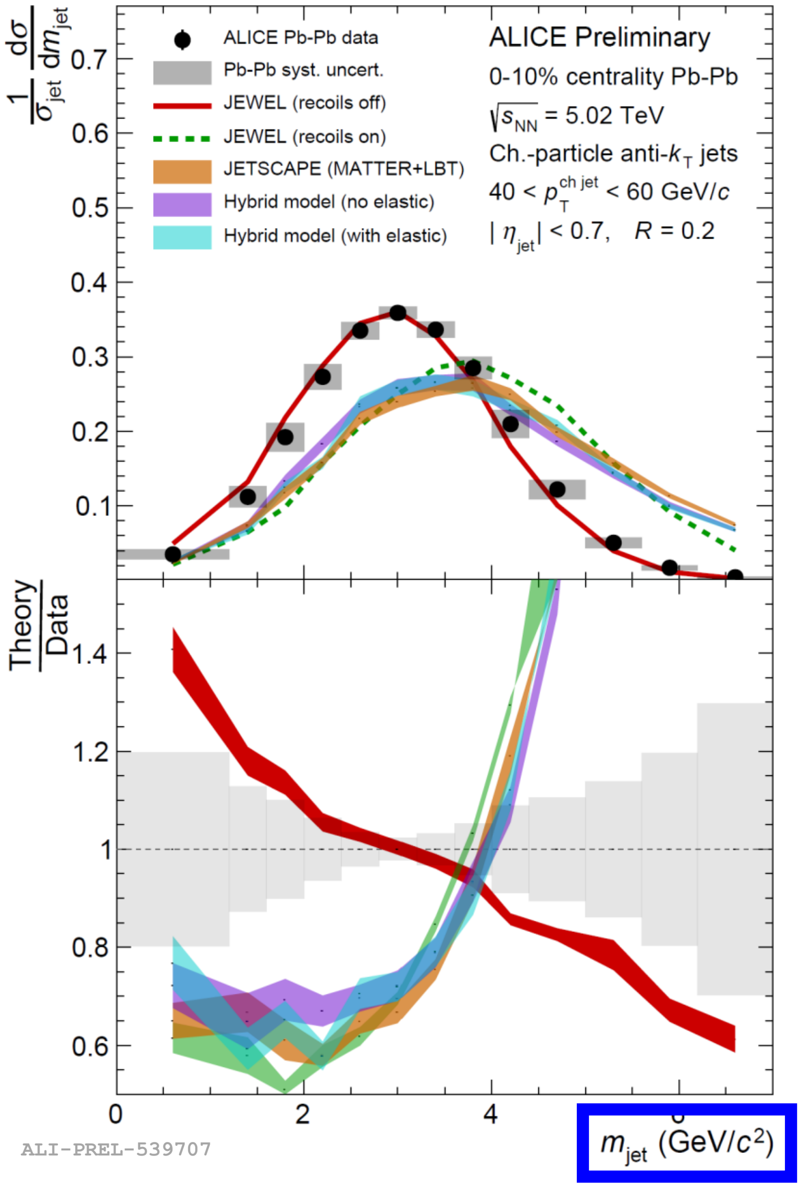


https://alice-figure.web.cern.ch/node/21570

$$\lambda_2 = \left(\frac{m}{Rp_{\text{T}}}\right)^2 + O[(\lambda_2)^2]$$

JHEP 1804 (2018) 110



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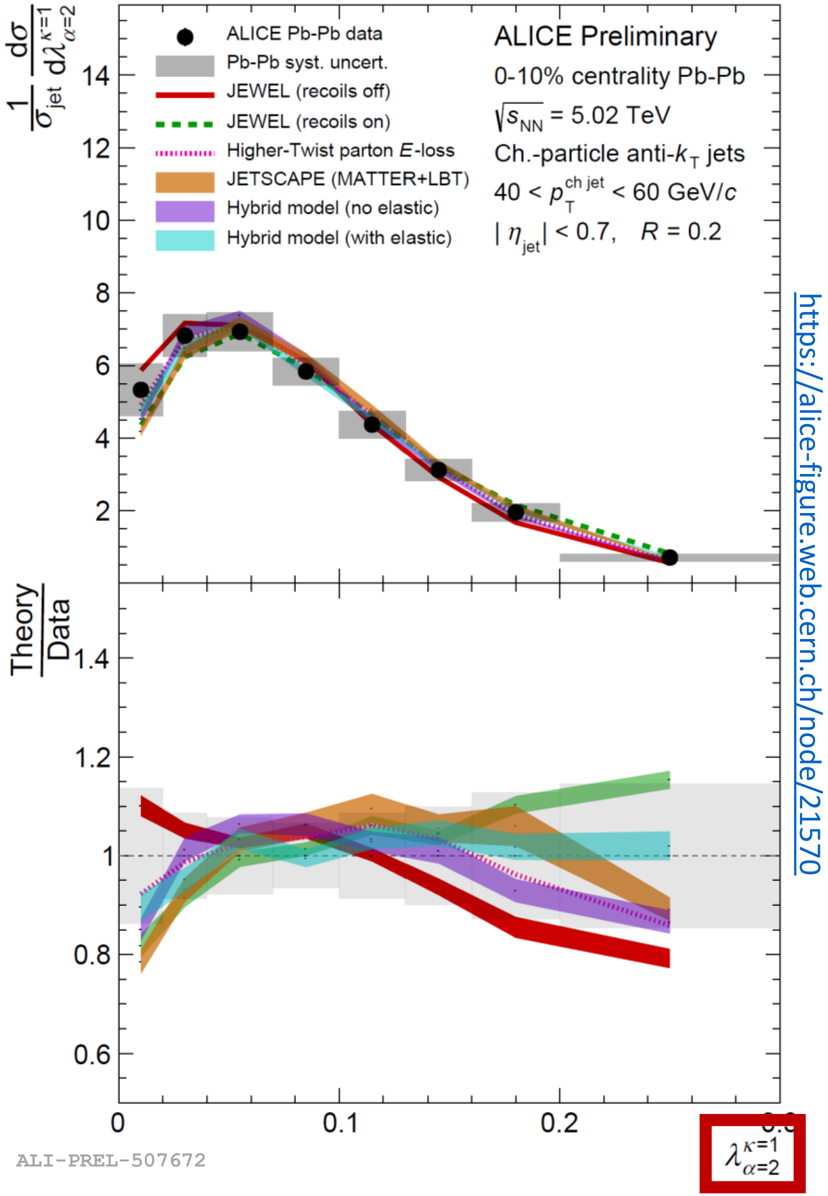

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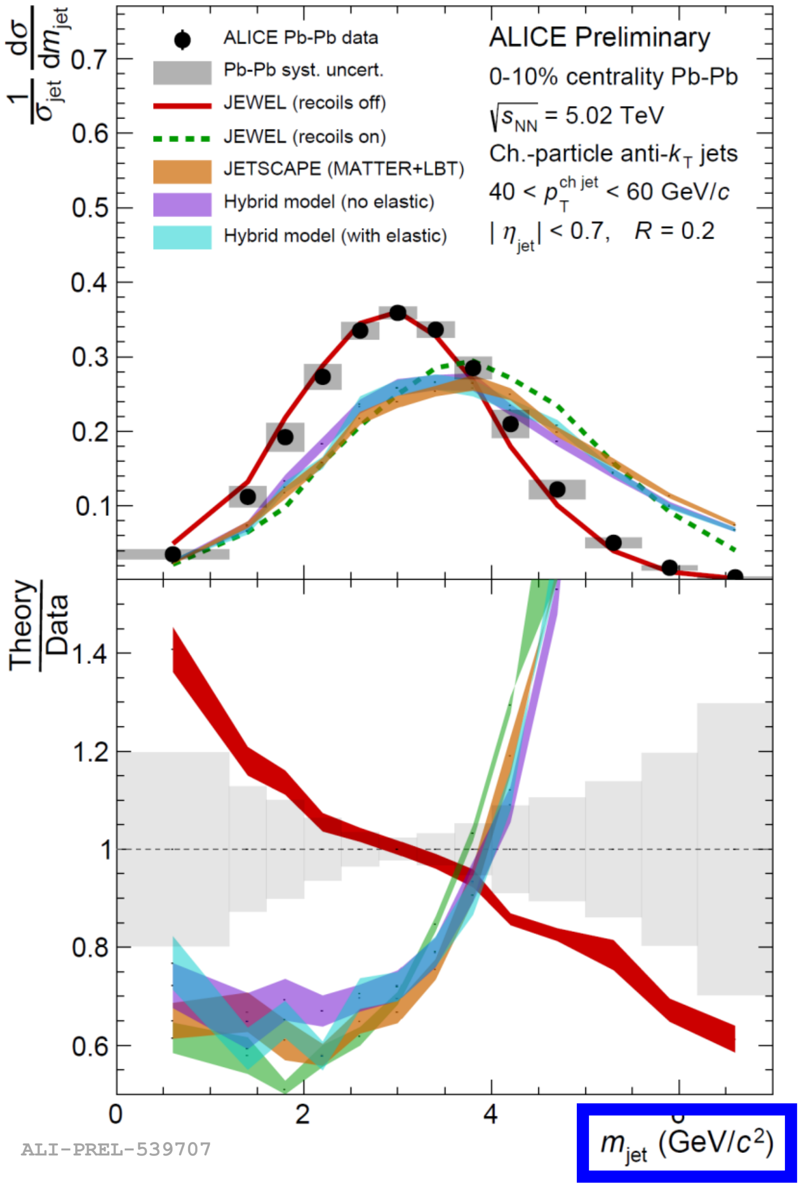
$$\lambda_2 = \left(\frac{m}{R p_T}\right)^2 + O[(\lambda_2)^2]$$

JHEP 1804 (2018) 110

- Many models show **25% shift in $\bar{m}_{\text{jet}}$** despite **great agreement in λ_2**



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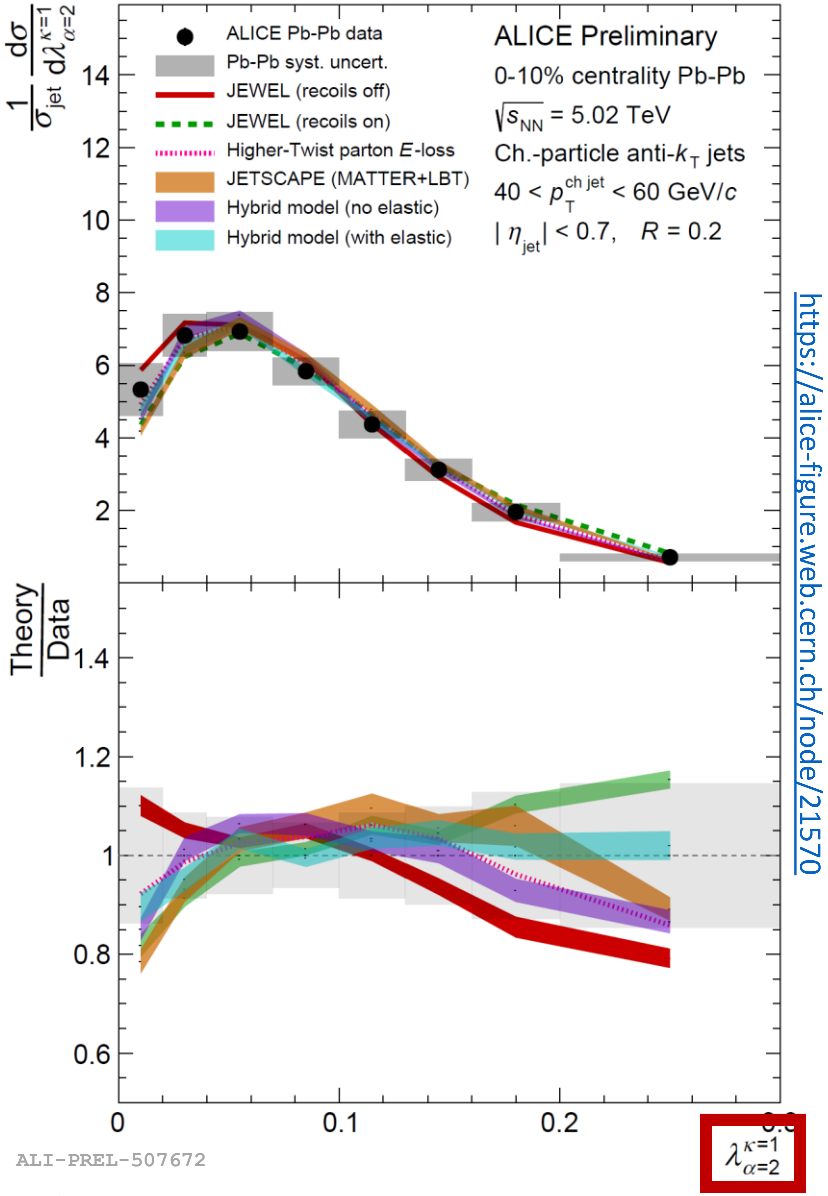

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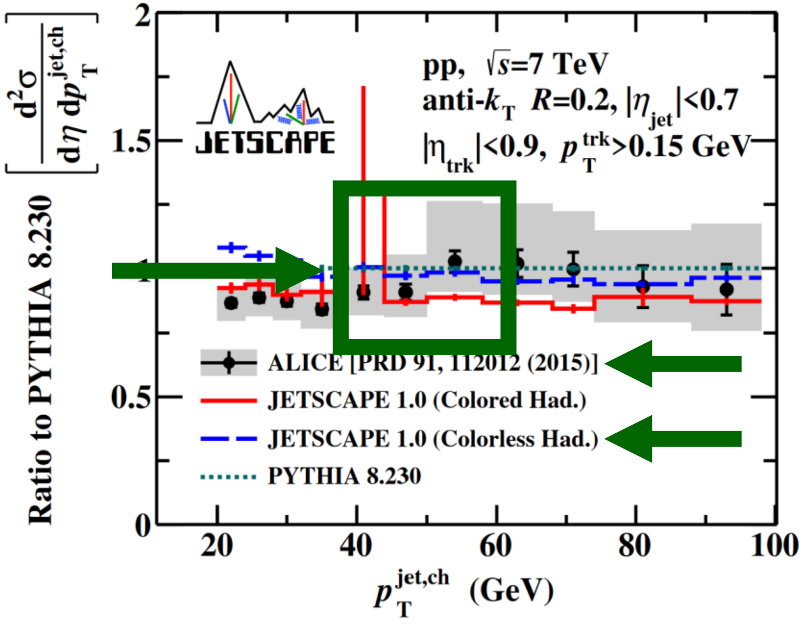
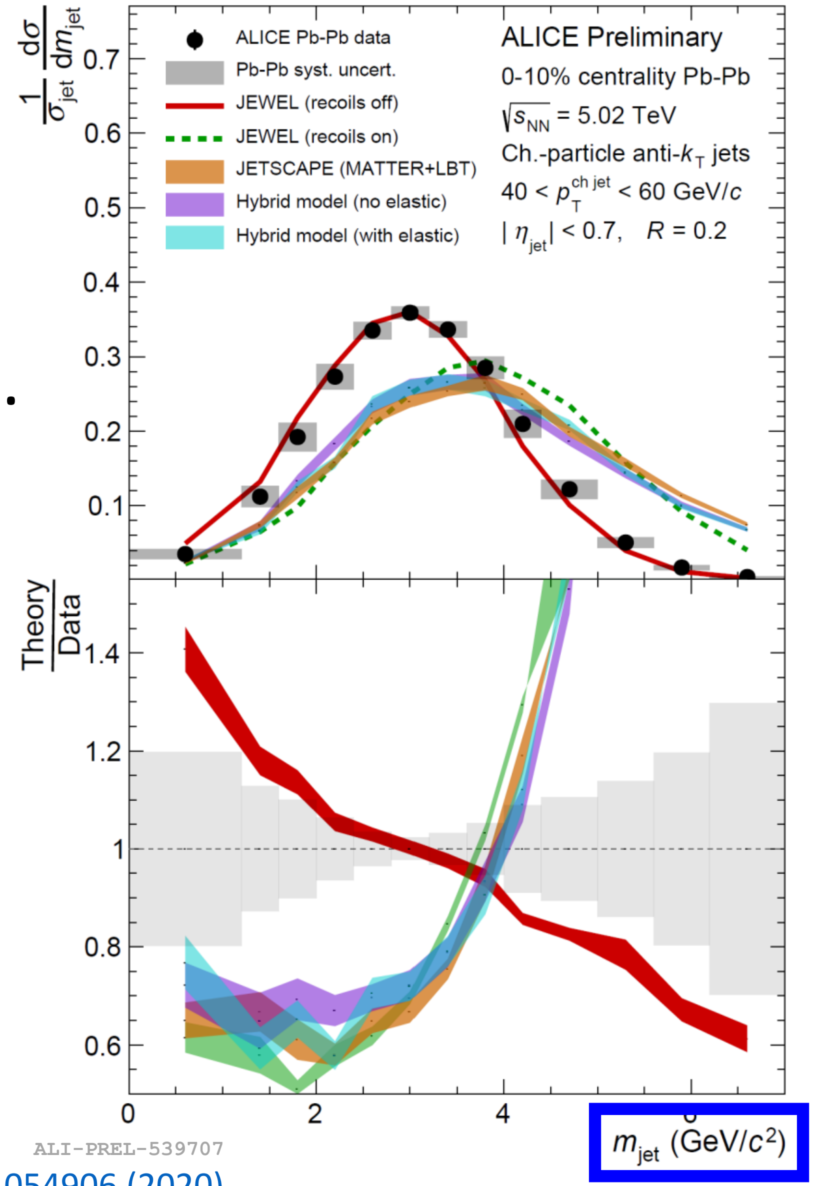
$$\lambda_2 = \left(\frac{m}{R p_T}\right)^2 + O[(\lambda_2)^2]$$

JHEP 1804 (2018) 110

- p_T **cross section** is often reproduced very well, e.g. in JETSCAPE:



Phys. Rev. C 102, 054906 (2020)



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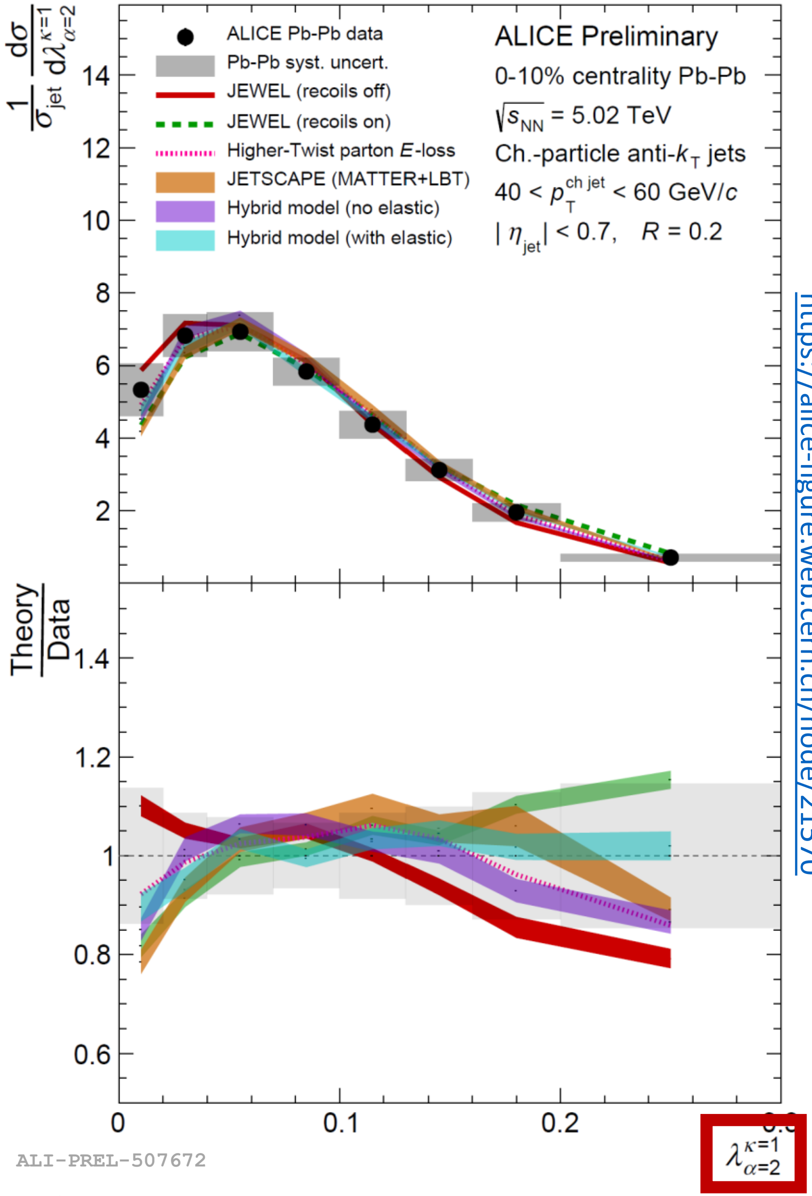


https://alice-figure.web.cern.ch/node/21570

$$\cancel{\lambda_2 = \left(\frac{m}{R p_{\text{T}}}\right)^2 + O[(\lambda_2)^2]}$$

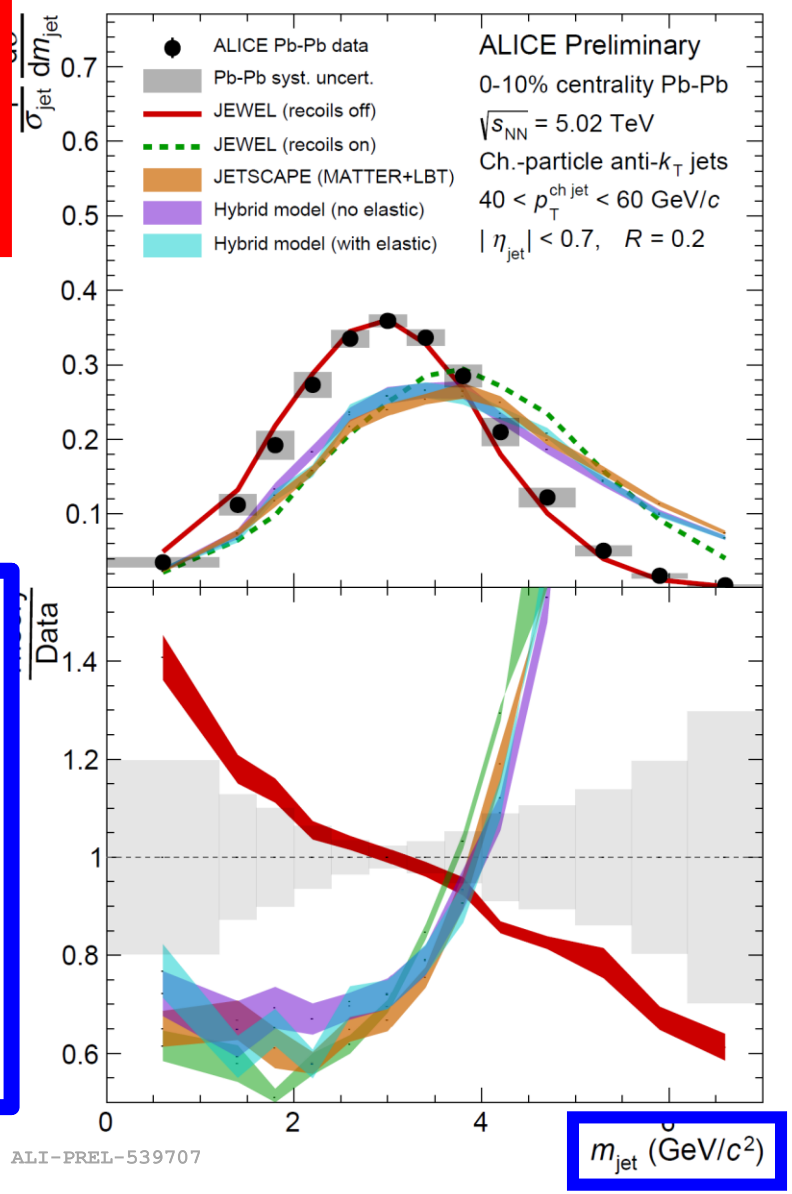
~~JHEP 1804 (2018) 110~~

Not useful for low-p_{T} jets

- **Resolves the girth-mass difference found in Run 1**

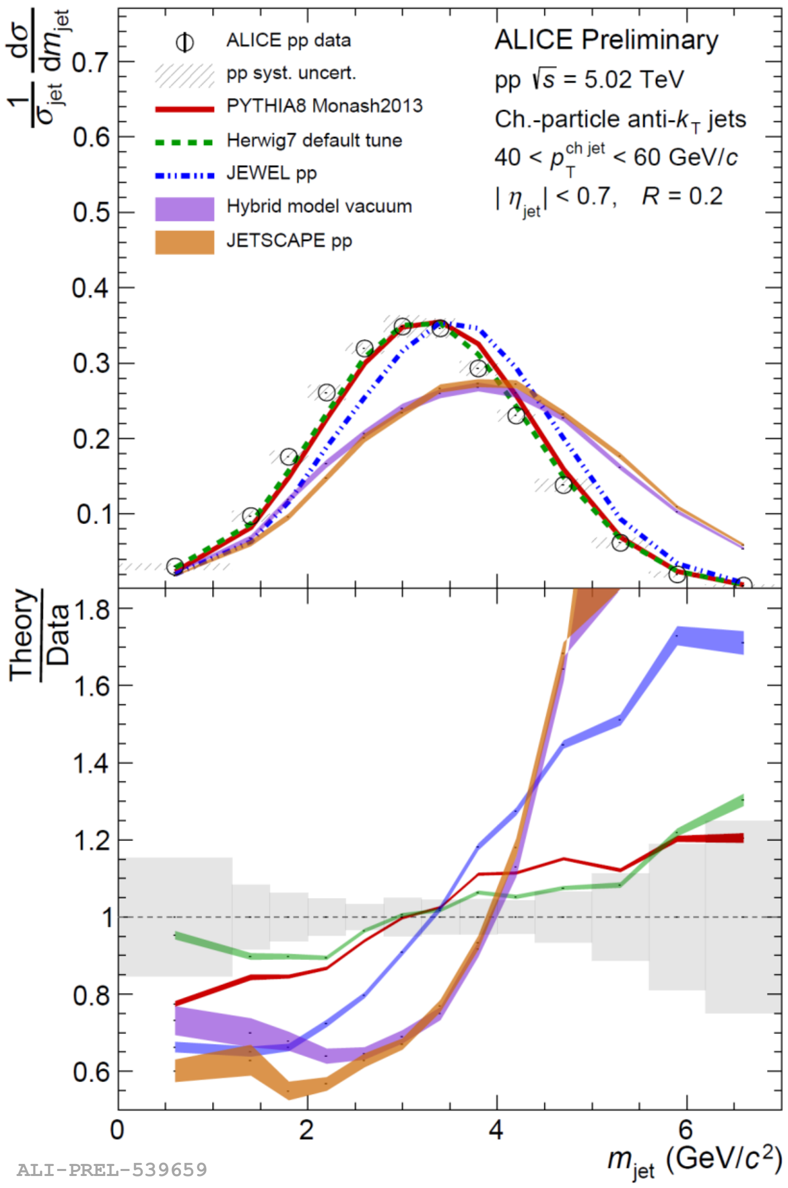
Lesson 2:

Closely related observables can have very different physics sensitivities



NEW!

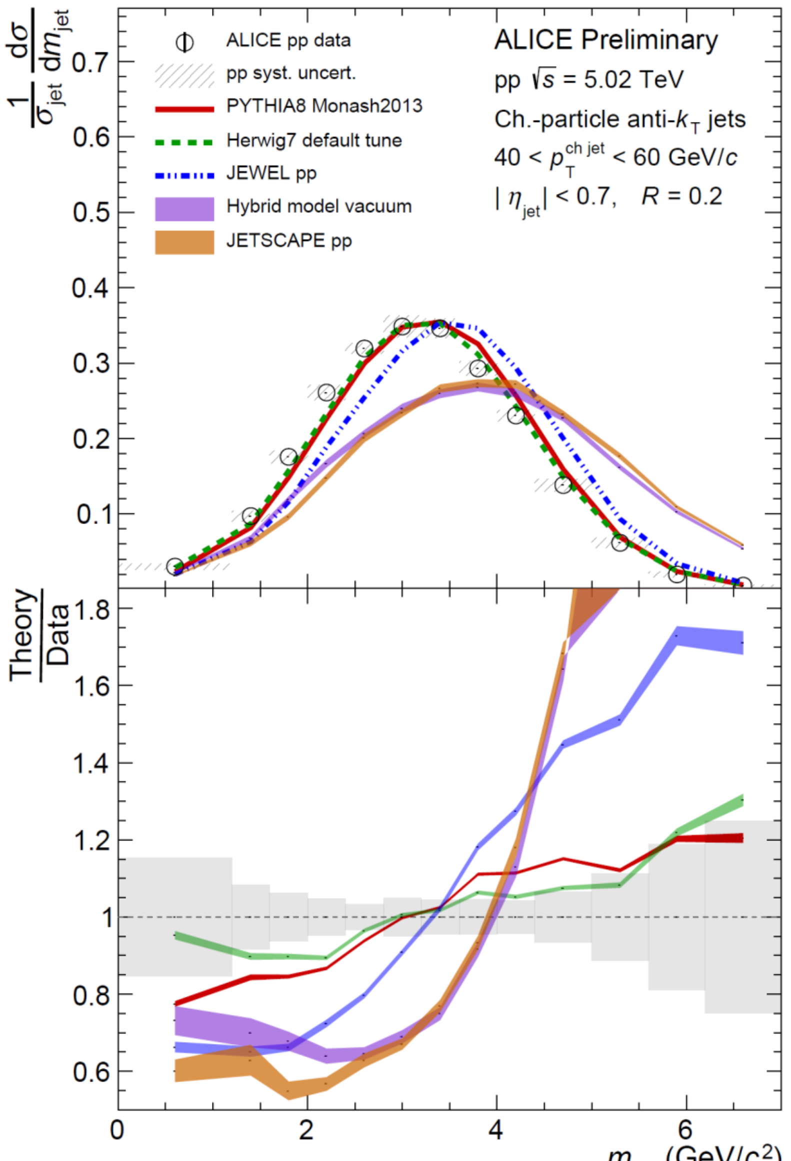
Jet mass compared to pp baseline



- Many models have same shift in pp baseline as AA

NEW!

Jet mass compared to pp baseline



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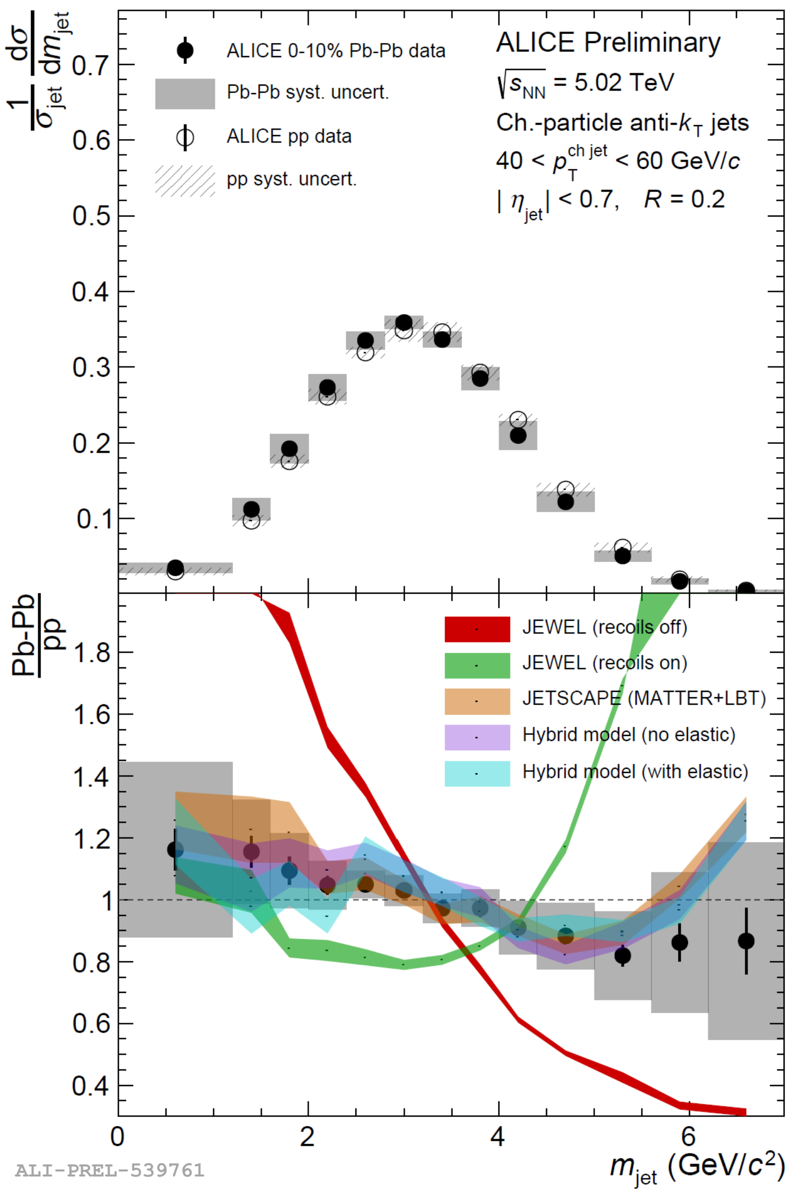
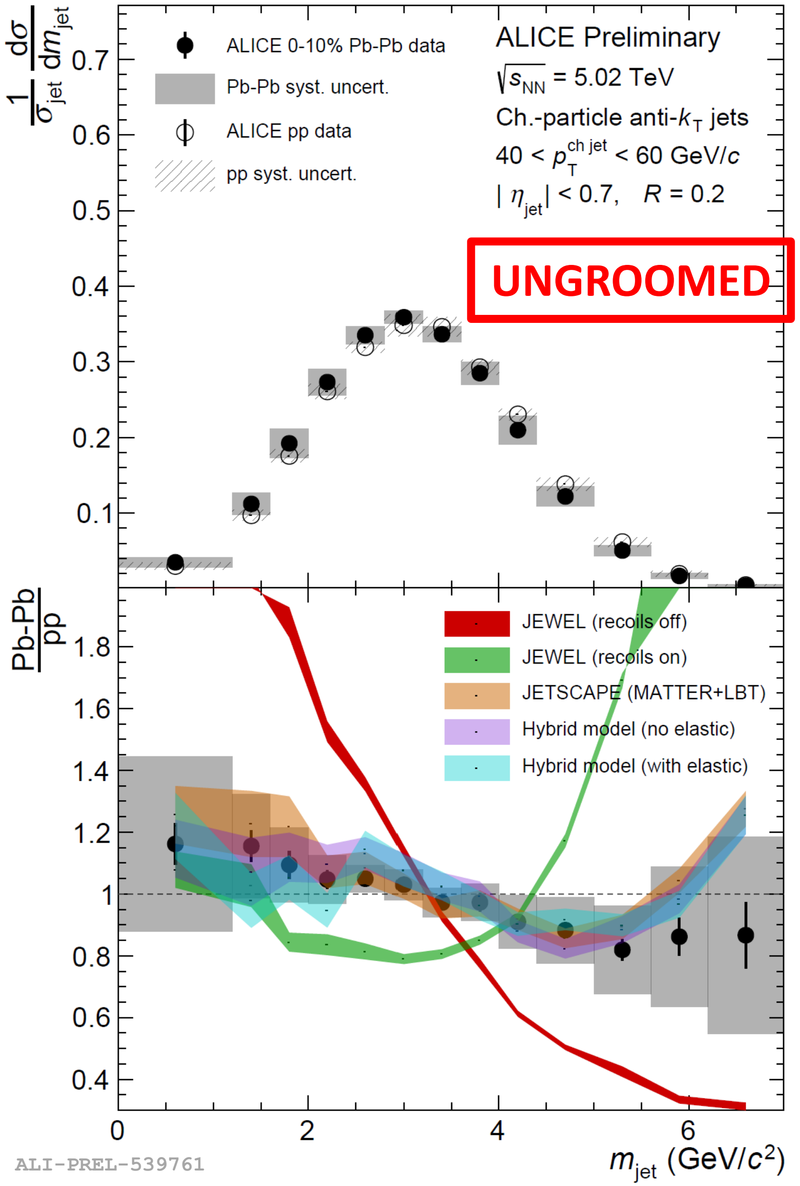


ALI-PREL-539761

- Despite some tenuous individual comparisons, **most models describe the quenching effect well**
- Possible shift towards low mass → **jet narrowing,** consistent with enhanced partonic virtuality depletion in-medium

NEW!

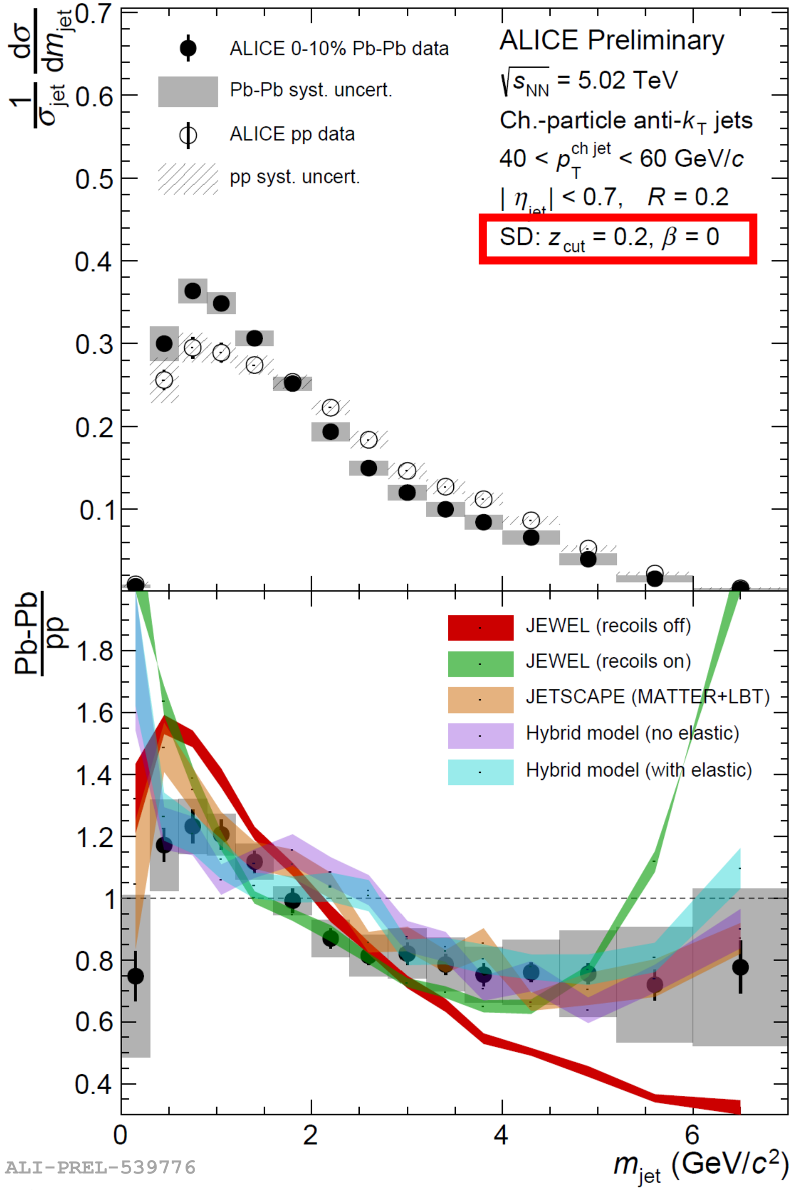
Jet mass compared to pp baseline



- **What about the effects of jet grooming?**
  - Employ Soft Drop to remove soft, wide-angle radiation
  - Calculate mass using remaining constituents

NEW!

Jet mass compared to pp baseline



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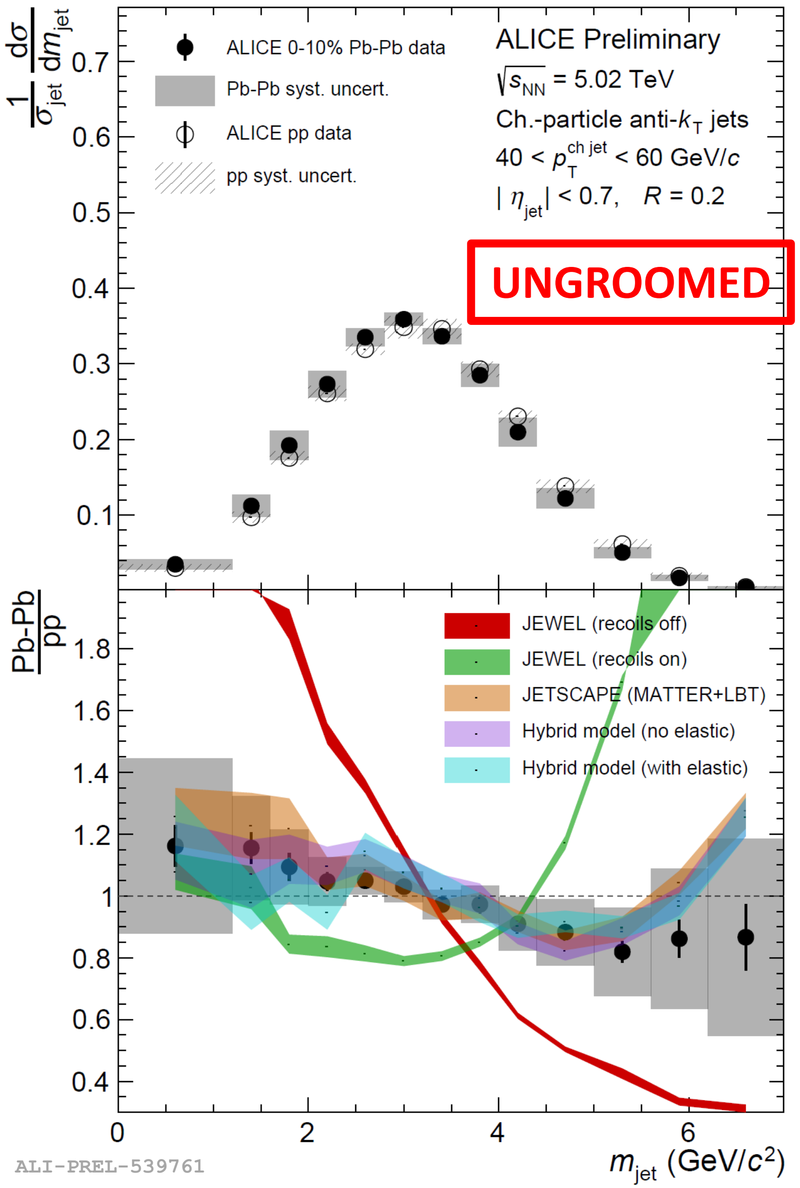

UNGROOMED

ALI-PREL-539761

Lesson 3:

- **Grooming enhances sensitivity to jet fragmentation modifications**

- Possible reasons:
  - Quark vs. gluon jets
  - SD removes soft background from jet
  - Jet core is modified
- Shape diff. (gr. vs. ungr.) is not so exaggerated in some models

There’s much to learn from Pb-Pb substructure…

- Some lessons from Run 2 jet angularity & jet mass measurements:
  1. **Comparison to a vacuum baseline is essential for interpreting these results**
  2. **Closely related observables can have very different physics sensitivities**
  3. **Grooming enhances sensitivity to jet fragmentation modifications**

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  - Possibility of enhancement with **jet grooming** conditions applied

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- ALICE presents here a suite of substructure observables that can be used to constrain models in pp and AA
  - **Improving models’ pp baselines will improve AA predictive power**

Many complementary studies by ALICE at HP2023:

- **Mass / dead cone** effects on the jet angularities
  → D^0-tagged jets: talk by **Preeti Dhankher** tomorrow at 11:10 (*link*)

- Other **groomed, fragmentation-dependent** observables
  → Groomed k_{T}: talk by **Raymond Ehlers** this morning at 11:10 (*link*)

- Transverse **components of the jet constituent momenta**
  → j_{T}: poster by **Jaehyeok Ryu** this evening at 18:15 (*link*)

- Substructure of inclusive vs. **high-multiplicity leading jets**
  → z: poster by **Debjani Banerjee** this evening at 18:15 (*link*)

- **Integrated grooming effects** and **in-jet correlations**
  → ΔR_{axis} and EEC: talk by **Rey Cruz-Torres** later this session (*link*)

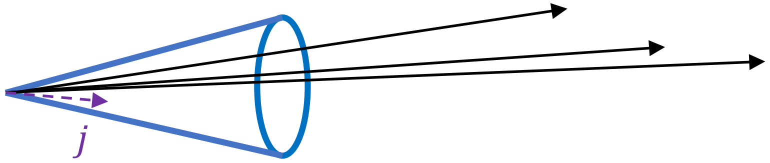
Backup

What is IRC safety?

$$\lambda_\alpha^\kappa \equiv \sum_{i\in\text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}}\right)^\kappa \left(\frac{\Delta R_{\text{jet},i}}{R}\right)^\alpha \equiv \sum_{i\in\text{jet}} z_i^\kappa \theta_i^\alpha$$

- Stands for Infra-Red and Collinear (IRC) safety
- Class of reconstruction algorithms & observables which satisfy certain conditions in order to avoid singularities from appearing in a well-defined path towards theoretical calculation

Infra-Red safety: the observable should not change if an infinitely-low-momentum particle is added to the event/jet



$$\lambda_{\alpha,\text{new}}^\kappa = \sum_{i\in\text{jet}} z_i^\kappa \theta_i^\alpha + z_j^\kappa \theta_j^\alpha$$

$$z_j = 0 \rightarrow z_j^\kappa \theta_j^\alpha = 0 \quad (\kappa > 0)$$

$$\lambda_{\alpha,\text{new}}^\kappa = \lambda_{\alpha,\text{old}}^\kappa$$

Collinear safety: the observable should not change if one particle splits into two collinear particles

$$\lambda_{\alpha,\text{new}}^\kappa = \sum_{(i\neq j)\in\text{jet}} z_i^\kappa \theta_i^\alpha + (\lambda z_j)^\kappa \theta_j^\alpha + [(1-\lambda) z_j]^\kappa \theta_j^\alpha$$

Need $\lambda^\kappa + (1-\lambda)^\kappa = 1 \quad \forall\{\lambda \in [0,1]\} \quad \rightarrow \quad \kappa = 1$

Consider 1-particle jet: $\lambda_{\alpha,\text{new}}^\kappa = (\lambda z_j)^\kappa \theta_j^\alpha + [(1-\lambda) z_j]^\kappa \theta_j^\alpha$

$$\theta_j = 0 \rightarrow z_j^\kappa \theta_j^\alpha = 0 \quad (\alpha > 0)$$

Charged-particle jet observables

- Charged-particle jets are useful for substructure observables since tracking detectors give **enhanced spatial precision**
- However, track-based observables are IRC-unsafe
- Formalism to calculate these observables using **track functions**†
- Currently we use the IRC-safe observables to motivate our measurements, and then apply nonperturbative corrections using different methods

† *H. Chang, M. Procura, J. Thaler, W. Waalewijn*
Phys. Rev. Lett. 111 (2013) 102002